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A HEAD-UP DISPLAY SYMBOLOGY EVALUATION FOR AN AUTONOMOUS LANDING GUIDANCE SYSTEM

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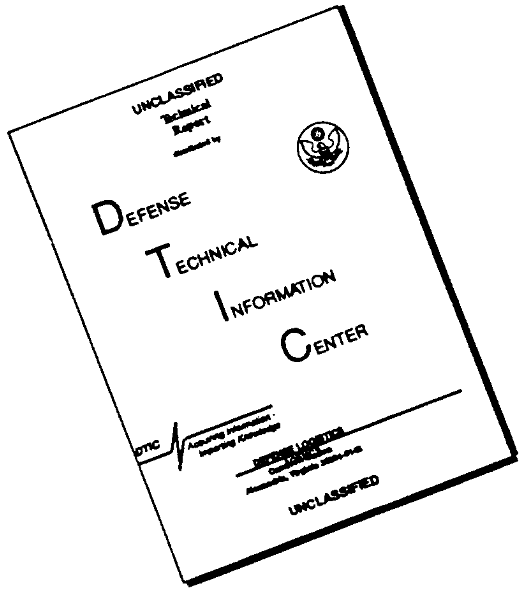

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13. ABSTRACT *(Maximum 200 words)*

A consortium of government agencies and major defense contractors has been assembled for the Autonomous Landing Guidance (ALG) Program. The purpose of the ALG program is to develop a prototype system that will integrate a variety of existing defense technologies to augment landing, take-off, and ground operations in low-visibility conditions, particularly on runways that are neither equipped nor approved for Category (CAT) II or III precision approaches. The Advanced Cockpits Branch of Wright Laboratory (WL/FIGP) supported the consortium by addressing pilot-vehicle interface issues associated with the integration of ALG into aircraft cockpits. WL/FIGP conducted a study investigating the integration of symbology and sensor imagery on the head-up display (HUD) in an ALG-equipped aircraft. A variety of HUD symbology sets were evaluated under a number of sensor/visibility conditions using WL/FIGP's Transport Aircraft Cockpit (TRAC) simulator. Objective measures of pilot performance as well as subjective workload and acceptability ratings were collected and analyzed to determine the optimum integration of symbology and sensor imagery in the context of an ALG precision approach and landing.

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ACRONYMS, TERMS, AND ABBREVIATIONS

AFB	Air Force Base
AGL	Above Ground Level
AIM	Airman's Information Manual
ALG	Autonomous Landing Guidance
ANOVA	Analyses of Variance
CAT	Category
CDI	Course Deviation Indicator
CRT	Cathode Ray Tube
DME	Distance Measuring Equipment
DoD	Department of Defense
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FLIR	Forward Looking InfraRed
HUD	Head-Up Display
Hz	Hertz
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
MIL-STD	Military Standard
MMRW	Millimeter Wave Radar
Nm	Nautical miles
OTW	Out-the-Window
PVI	Pilot-Vehicle Interface
RMS	Root-Mean Square
RPI	Runway Point of Intercept
RVR	Runway Visibility Range
SWORD	Subjective WORkload Dominance
TRAC	Transport Aircraft Cockpit

TV	Television
VMC	Visual Meteorological Conditions
VV	Vertical Velocity
WAC	Wide Angle Collimated
WL/FIGP	Wright Laboratory Advanced Cockpit Branch

1. INTRODUCTION AND SUMMARY

The Autonomous Landing Guidance (ALG) Program is an effort aimed at providing commercial and military transports with the capability to perform approaches and landings in low-visibility conditions at airfields that are not equipped for such operations. An industry-government alliance was formed to develop an ALG prototype for transport aircraft. In support of the alliance, the Advanced Cockpits Branch of Wright Laboratory (WL/FIGP) conducted a study that will support the definition of head-up display (HUD) symbology and sensor imagery integration requirements for ALG applications in commercial and military transport aircraft. The background and objectives of this study are described in this section, as well as a summary of the methodology used and the study's findings.

1.1 Background

The concept of ALG systems is to use existing technologies, including HUDs, the Global Positioning System (GPS), forward looking infra-red (FLIR) sensor imagery, and millimeter wave radar (MMWR) sensor imagery to augment traditional landing aids in low-visibility conditions. The goal of the ALG program is to substantially expand low-visibility operations for both commercial and military aircraft. Consequently, the successful development of an ALG system will also provide greater operational flexibility for military operations. Specifically, an ALG system will allow special and tactical military operations to venture into austere or unprepared landing fields regardless of the weather conditions.

In the case of transport aircraft, the Federal Aviation Administration (FAA) defines five weather categories associated with low-visibility approach conditions using minimum ceiling and runway visibility values. Current regulations (Federal Aviation Regulations/Airman's Information Manual (FAR/AIM)) limit Category (CAT) II and CAT IIIa[1] approaches and

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[1] CAT II minimums: ≥1200 ft runway visibility range (RVR), 100 ft decision height; CAT IIIa minimums: 0 through 700 ft RVR, no decision height.

landings to runways that conform to strict Instrument Landing System (ILS), lighting, and obstruction clearance requirements. Because it is expensive to equip and maintain airfields for CAT II and CAT III operations, the vast majority of airfields are equipped for CAT I operations (≥1800 ft RVR, 200 ft decision height). Very few CAT II or CAT III facilities currently exist and the assumption is that few will be constructed. The use of an ALG system will allow both commercial and military aircraft to safely land at airfields equipped for CAT I operations in visibility conditions below the CAT I minimums.

1.2 Objectives

In an aircraft equipped for ALG, GPS-driven flight and approach guidance symbology and a sensor-generated image of the runway environment will be provided on a HUD, with the symbology superimposed over the sensor imagery. During a low-visibility precision approach with an ALG system, the pilot will use traditional navigation instruments to perform the initial approach, the GPS-driven HUD symbology throughout the approach, and the visual cues from the sensor image, rather than natural vision to perform a final landing decision.

Before an ALG HUD can serve as an effective pilot-vehicle interface (PVI), the symbology and the sensor imagery must provide the critical information required for a low-visibility precision approach. In addition, the HUD symbology must not unnecessarily clutter the display or obscure the important visual cues provided by the sensor imagery. Occasionally, these two requirements conflict. The addition of symbology may be desirable to provide important flight information, but the addition of the symbology may also contribute to clutter and masking of the sensor image. The HUD symbology requirements may also depend on the quality of the sensor image. WL/FIGP is addressing these issues through its cockpit research program. The three objectives of the ALG study were as follows:

- **Objective 1**

  Determine the relative effects of different symbology sets and their inherent levels of clutter on pilot performance, pilot acceptance, and pilot workload.

- **Objective 2**

  Determine the effect of sensor imagery on pilot performance, pilot acceptance, and pilot workload in an ALG context.

- **Objective 3**

  Identify "safe minimum" and "optimum" ALG HUD symbology sets.

1.3 Scope

This report describes the methodology and results of the study completed by WL/FIGP in support of the development effort for an ALG system. It also recommends HUD information and symbology requirements for an ALG system that are based on pilot performance, pilot workload, and pilot preferences. Finally, the report addresses requirements and considerations for future research. Study findings are presented to provide design guidance to ALG system designers and integrators, as well as to provide guidance for failure mode analyses.

1.4 Executive Summary

To accomplish the study's objectives, 12 pilots performed a flight simulation experiment, a HUD assembly experiment, and completed a questionnaire. In the flight simulation experiment, the pilots flew a series of precision approaches (referred to as the Precision Approach Task) using four experimental HUD Symbology Sets in four Sensor/Visibility Conditions. Pilot performance, pilot workload, and pilot acceptance ratings were collected during each precision approach. The four experimental HUD Symbology Sets were: 1) a symbology set that included a runway representation (the Basic Plus Runway Symbology Set or Basic/RWY); 2) a set that included raw deviation data (the Basic Plus Raw Deviation Data or Basic/RAW); 3) a set that had both raw data and a runway symbol (Basic/BOTH); and 4) a set composed of the full complement of symbology (the Full HUD). The four HUD Symbology Sets used in the study were based on the Sextant Avionique HUD format, with

each containing the minimum symbology required for basic instrument flying (airspeed, altitude, vertical velocity, flight path/pitch ladder, heading, and bank angle).

The four Sensor/Visibility Conditions represented various levels of visual image quality and were: 1) Visual Meteorological Conditions (VMC) providing an unlimited visibility, full field-of-view (FOV), daytime scene; 2) Instrument Meteorological Conditions (IMC) with a 25° x 35° FOV FLIR image on the HUD; 3) a Corner Reflector Condition representing a MMWR image of a series of corner reflectors outlining the runway; and 4) a No Sensor Condition representing CAT IIIa weather minimums with a 0 ft decision height and 700 ft RVR. In the Precision Approach Task, the pilots flew each combination of HUD Symbology Set and Sensor/Visibility Condition twice, totaling 32 approaches.

In the HUD assembly experiment, the pilots defined HUD symbology sets that would be required to complete a precision approach under a variety of Approach and Sensor/Visibility Conditions. For each condition, the pilots identified two sets of symbols. The first was the minimum symbology set the pilots thought would allow the safe completion of an approach. The second set included the minimum safe set and additional symbols the pilots selected to optimize the format. After the pilots finished both experiments, they completed a questionnaire (see Appendix A) that included a workload evaluation, as well as a variety of questions and rating scales regarding the HUD Symbology Sets. The data were used to compare pilot workload across the test conditions and to aid interpretation of the performance data.

WL/FIGP conducted the experiments in the Transport Aircraft Cockpit (TRAC) flight simulator, a fully reconfigurable research simulator containing two crew positions (pilot and co-pilot) and a third station for the test engineer. Wide-angle collimated (WAC) displays mounted directly in front of each crew position dynamically displayed the HUD Symbology Sets and Sensor/Visibility Conditions.

Analyses of Variance (ANOVA) and the appropriate post-hoc tests were applied to the performance and workload data collected in the Precision Approach Task. For the subjective data, including the symbology selections from the HUD Assembly Task, frequency distributions and means were calculated and comments were summarized.

During the precision approaches, the pilots performed least accurately and rated workload highest with the Basic/RWY (the least amount of approach information) and the Full HUD (the greatest amount of approach information) Symbology Sets. Conversely, pilots performed most accurately and rated workload lowest for the Basic/RAW and Basic/BOTH Symbology Sets. On the questionnaires, the pilots commented that the Basic/RWY did not provide adequate information to safely complete the approach, and that the Full HUD presented too much information and was too cluttered. The clutter and high symbology density associated with the Full HUD caused distraction and obscured the sensor/visual image. Finally, the pilots landed closer to the designated touchdown point in the VMC and FLIR Conditions, than they did in the Corner Reflector or No Sensor Conditions.

In the HUD Assembly Task, the pilots identified symbology sets resembling the Basic/RAW Symbology Set for both the minimum and optimum formats. With the exception of groundspeed and the aircraft reference symbol, the pilots retained all of the symbology from the Basic format. For the minimum set, more than half the pilots added a selected course indicator, the digital distance measuring equipment (DME), and course deviation symbology to the Basic Symbology Set. For the optimum set, more than half the pilots selected the symbols included in the minimum set and added a flight director for the long final situations. They added a wind vector symbol, a rising runway, and the perspective runway symbol for the short final situations. These results are consistent with the findings of the performance and workload analyses.

The recommended optimum HUD Symbology Sets provide design guidelines for ALG system designers that are consistent with the HUD symbology requirements and recommendations identified in military standards and previous research (MIL-STD-1787;

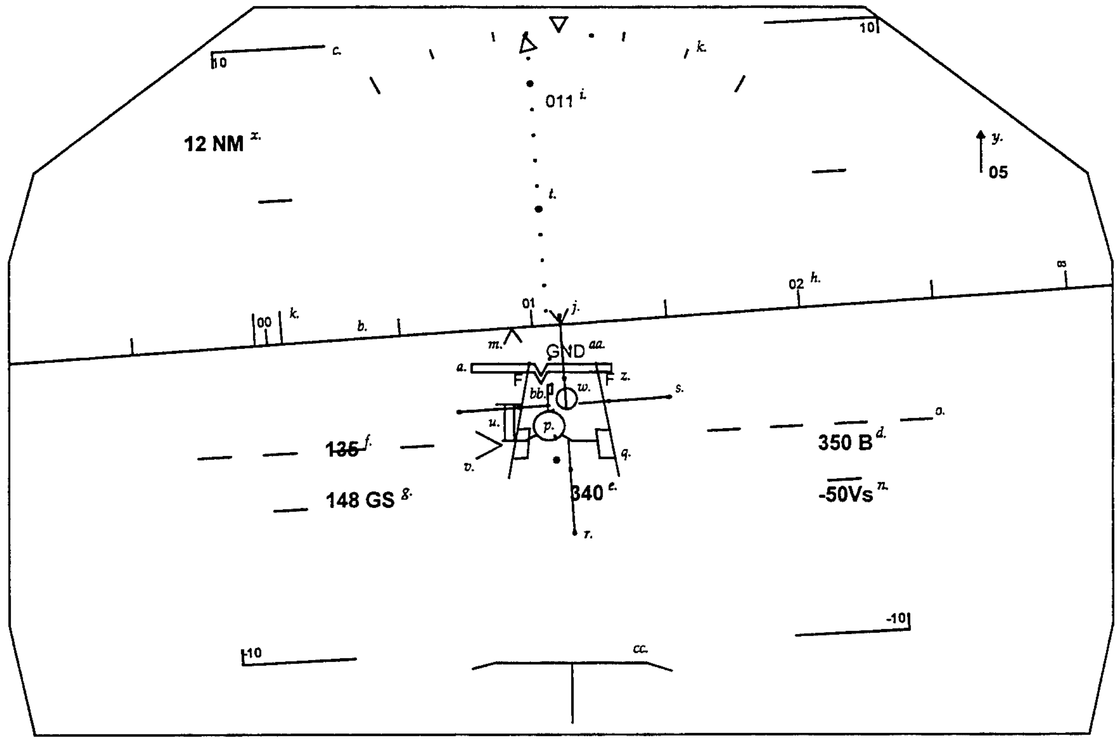
Todd et al., 1993). The minimum safe set provides a starting point for defining declutter options. The findings also indicated that in low-visibility situations, sensor imagery of sufficient quality presented on the HUD will elicit performance that approaches that achieved in VMC.

2. THE HUD SYMBOLOGY SETS

Pilots flew four different Symbology Sets in the evaluation: 1) the Basic Plus Runway Symbology Set, 2) the Basic Plus Raw Deviation Data Symbology Set, 3) the Basic Plus Both Runway and Raw Deviation Data Symbology Set, and 4) the Full Head-Up Display (HUD). All of the sets were variations of the Sextant Avionique HUD format (Coirier, 1995). The Sextant format is currently used only in commercial aircraft applications, but is representative of the information content and formats currently implemented in military transport aircraft. This study was not intended to be a critical evaluation of the Sextant HUD, but rather an information requirements definition exercise with the Sextant HUD serving as the test symbology set. The Sextant HUD is similar to other HUDs and was chosen due to its exposure within the Autonomous Landing Guidance (ALG) industry-government alliance and the availability of the specifications necessary to incorporate its symbology into the Transport Aircraft Cockpit (TRAC) simulator.

The test Symbology Sets included basic symbology that provided information required for instrument flight, including a flight path marker and scale, pitch, bank, airspeed, barometric altitude, radar altitude, ground speed, vertical velocity, and heading. This symbol set, referred to as the "Basic Symbology Set," conforms to the military's primary flight display requirements for instrument flying (MIL-STD-1787B). The test Symbology Sets were selected based on an analysis of the information requirements associated with a precision approach and the differences in the quantity and precision of the approach information they provided.

The following sub-sections describe the test Symbology Sets and include an image of each as obtained from the simulation. Each of the individual symbols can be identified using the representative schematic of the HUD (see Figure 1). The schematic (Figure 1) provides an identity to each of the HUD symbols discussed in this report.



a. Aircraft Reference
b. Horizon Line
c. Vertical Scale
d. Digital Barometric Altitude
e. Digital Radar Altitude
f. Digital Airspeed (Actual)
g. Groundspeed
h. Heading Scale
i. Digital Heading
j. Actual Heading Marker
k. Selected Heading Marker
l. Roll Scale
m. Actual Track Marker
n. Digital Vertical Speed
o. Selectable Vertical Reference
p. Flight Path Marker
q. Runway
r. Raw Azimuth Deviation
s. Raw Elevation Deviation
t. Selected Course
u. Speed Error Tape
v. Acceleration Cue
w. Flight Path Guidance Cue
x. Distance Measuring Equipment
y. Wind Vector
z. Flare Annunciator
aa. Landing Advisory
bb. Flight Yaw Indicator
cc. Rising Runway

Figure 1. HUD Symbology Schematic

2.1 The Basic Plus Runway Symbology Set

The Basic Plus Runway Symbology Set (Basic/RWY), as shown in Figure 2, included the Basic Symbology Set and a perspective runway outline, providing the approach guidance. The runway symbol dynamically provided gross lateral and vertical guidance and gross distance to the runway, which was based on the position and orientation of the aircraft with respect to the airstrip. In theory, the runway symbol is intended to provide the same visual cues (e.g., perspective and orientation information) as a visual scene of the runway

environment. Previous researchers (Todd, et al., 1993) suggested that a perspective runway symbol may be able to serve as an intuitive substitute for traditional HUD approach symbology, including raw deviation data and flight director information. In this study, the runway symbol represented the minimum approach symbology provision as it provided the least and lowest-precision approach information. The Basic/RWY Symbology Set also had the least symbology and, consequently, the least clutter.

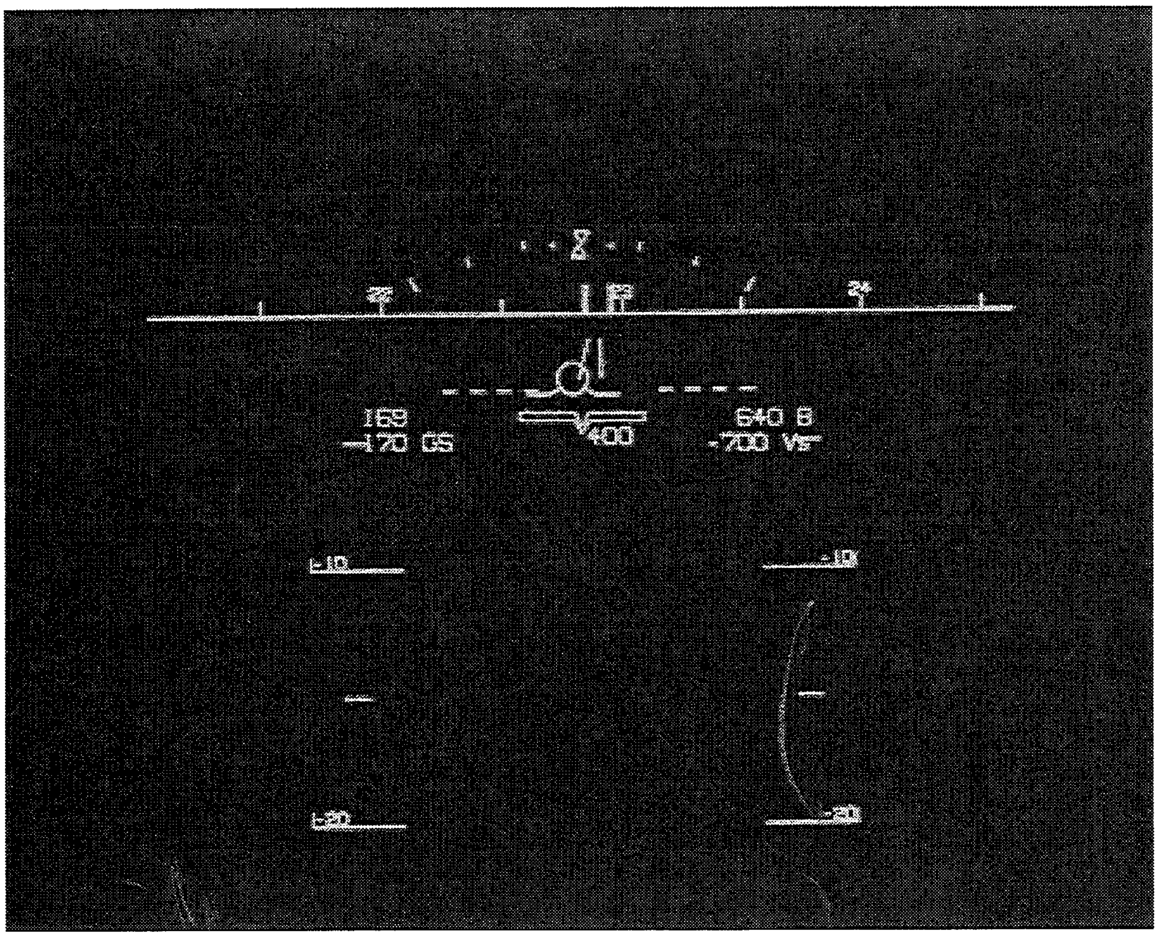


Figure 2. The Basic Plus Runway HUD Symbology Set

2.2 The Basic Plus Raw Deviation Data Symbology Set

The Basic Plus Raw Deviation Data Symbology Set (Basic/RAW), as shown in Figure 3, included the Basic Symbology Set along with raw azimuth and glideslope deviation symbols. The runway symbol was not part of this symbology set. This set included approach symbology that has traditionally been provided by head-up and head-down display formats. Relative to the other Symbology Sets, the Basic/RAW Symbology Set consisted of a moderate quantity of symbology, a moderate level of clutter, and high-precision approach information.

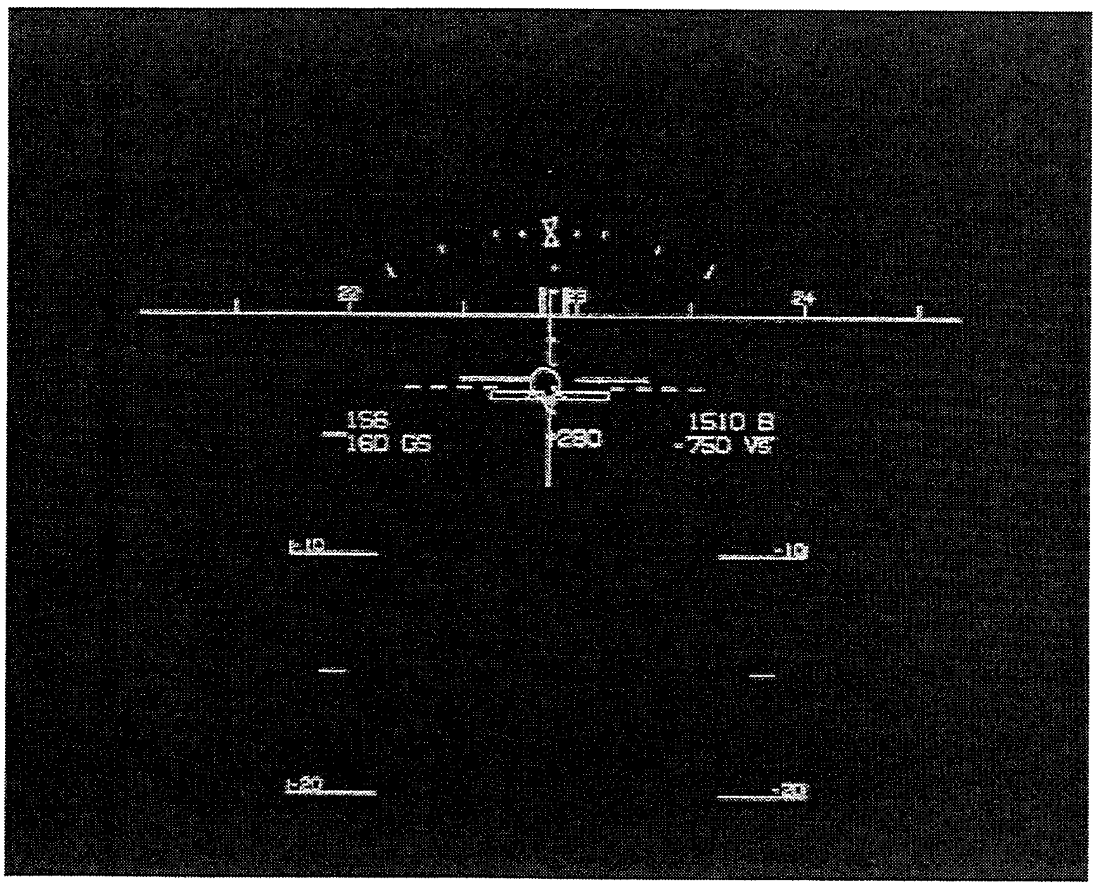


Figure 3. The Basic Plus Raw Deviation Data HUD Symbology Set

2.3 The Basic Plus Both Runway and Raw Deviation Data Symbology Set

The Basic Plus Both Runway and Raw Deviation Data Symbology Set (Basic/BOTH) was identical to the Basic/RAW Symbology Set, except for the addition of the perspective runway, as shown in Figure 4. It provided both the traditional, high-precision approach information, as well as the intuitive visual cues provided by the runway symbol in the same format. Because it provided both symbols, the Basic/BOTH HUD included slightly more symbology and clutter than the Basic/RWY and the Basic/RAW Symbology Sets.

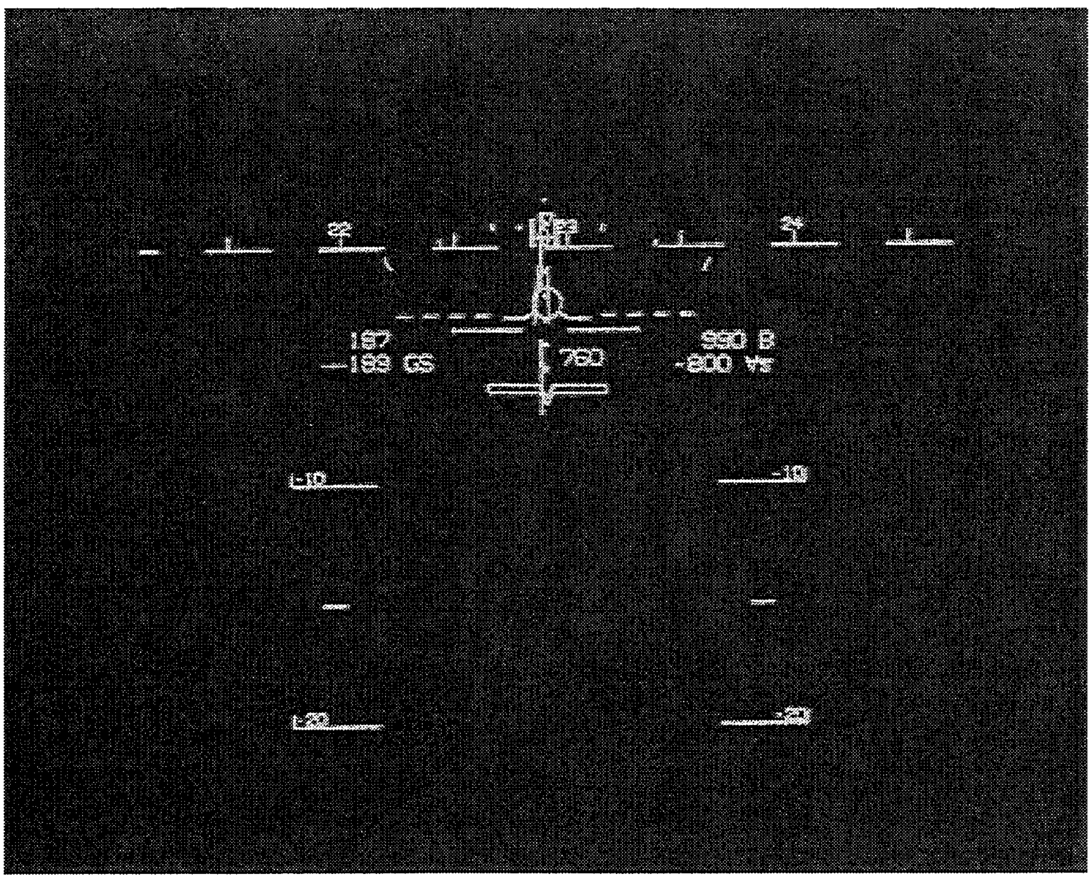


Figure 4. The Basic Plus Both Runway & Raw Deviation Data HUD Symbology Set

2.4 The Full Sextant HUD

The Full Sextant HUD (Full HUD) included every symbol identified in the Sextant specification (Coirier, 1993). The Full HUD was included in the evaluation to represent the condition in which maximum information is available. The Full HUD is shown in Figure 5, and the HUD Symbology Sets and their respective symbols are summarized in Table 1. Some of the symbols in Table 1 (those accompanied by an asterisk) are *not* shown in the HUD schematic (Figure 1) or any of the HUD Symbology Set images (Figures 2, 3, 4, and 5). Because they were either mode status indicators or symbols identifying extreme situations, these symbols were rarely, if ever, displayed. As such, they had little or no relevance in this study and were not formally evaluated.

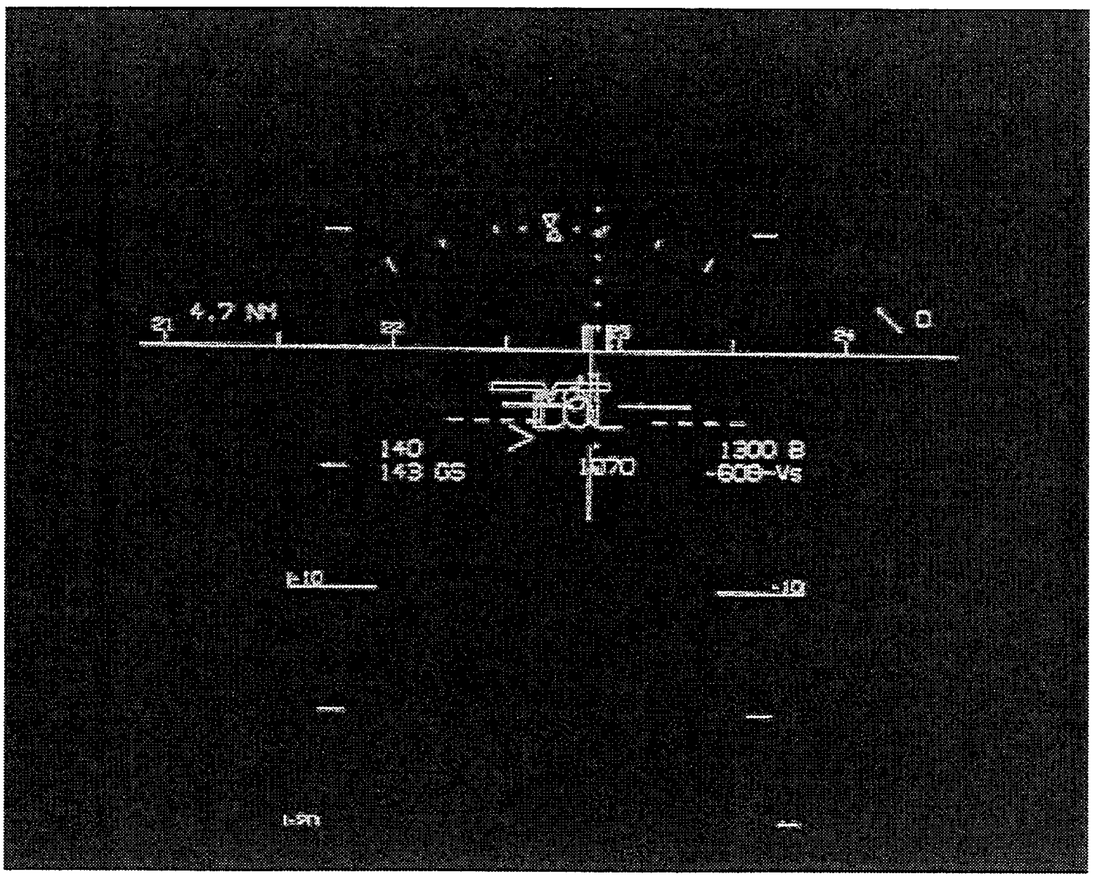


Figure 5. The Full Sextant HUD Symbology Set

Table 1. The HUD Symbology Sets

HUD Symbology Elements	Basic/RWY	Basic/RAW	Basic/BOTH	Full HUD
Aircraft Reference	X	X	X	X
Horizon Line & Vertical Scale	X	X	X	X
Digital Barometric and Radio Altitudes	X	X	X	X
Digital Airspeed (actual) and Groundspeed	X	X	X	X
Heading Scale with Digital Heading, Actual and Selected Heading Markers	X	X	X	X
Roll Scale	X	X	X	X
Actual Track Marker	X	X	X	X
Digital Vertical Speed	X	X	X	X
Flight Path Marker	X	X	X	X
Runway	X		X	X
Raw Azimuth Deviation		X	X	X
Raw Elevation Deviation		X	X	X
Selected Course		X	X	X
Speed Error Tape & Acceleration Cue				X
Vertical, Horizontal, & Steady Flight Director Mode *				X
Flight Path Guidance Cue				X
Digital Distance Measuring Equipment (DME)				X
Wind Vector				X
Course Markers *				X
Retard & Flare Annunciators				X
Roll & Angle of Attack Limits *				X
Landing Advisory				X
Flight Yaw Indicator				X
Selectable Vertical Reference				X
EVS Status *				X
Over Flare Caution *				X
Centerline Lateral Guidance *				X
To/From Indicator *				X
CDI Needle *				X
Rising Runway				X

3. THE SENSOR/VISIBILITY CONDITIONS

The pilots flew each head-up display (HUD) Symbology Set in four computer generated Sensor/Visibility Conditions: 1) Visual Meteorological Conditions (VMC), 2) Instrument Meteorological Conditions (IMC) with forward looking infrared (FLIR) Sensor, 3) IMC with millimeter wave radar (MMWR) Sensor, and 4) IMC with No Sensor. These Sensor/Visibility Conditions were displayed as out-the-window (OTW) scenes on the Transport Aircraft Cockpit (TRAC) simulator's wide-angle collimated (WAC) windows, along with the HUD symbology. The four Sensor/Visibility Conditions represented baseline visibility, as well as two levels of sensor image quality. The two sensor conditions reflected characteristic sensor performance requirements to which Autonomous Landing Guidance (ALG) systems are being designed. In all of the Sensor/Visibility Conditions, the images were detailed representations of two actual airfields located at US Air Force Bases (AFBs): Pope AFB (used exclusively in the training sessions) and McGuire AFB (used in the data collection sessions). Both airfields were constructed from the published approach plates (Department of Defense (DoD) Flight Information Publication (Terminal)) and included the runways, taxiways, and lighting systems, as well as the control tower, hangers, and other structures at the field.

3.1 Visual Meteorological Conditions

The depiction of Visual Meteorological Conditions (VMC) consisted of a simulated full color visual scene with unlimited visibility. VMC was included for baseline comparisons (see Figure 6).

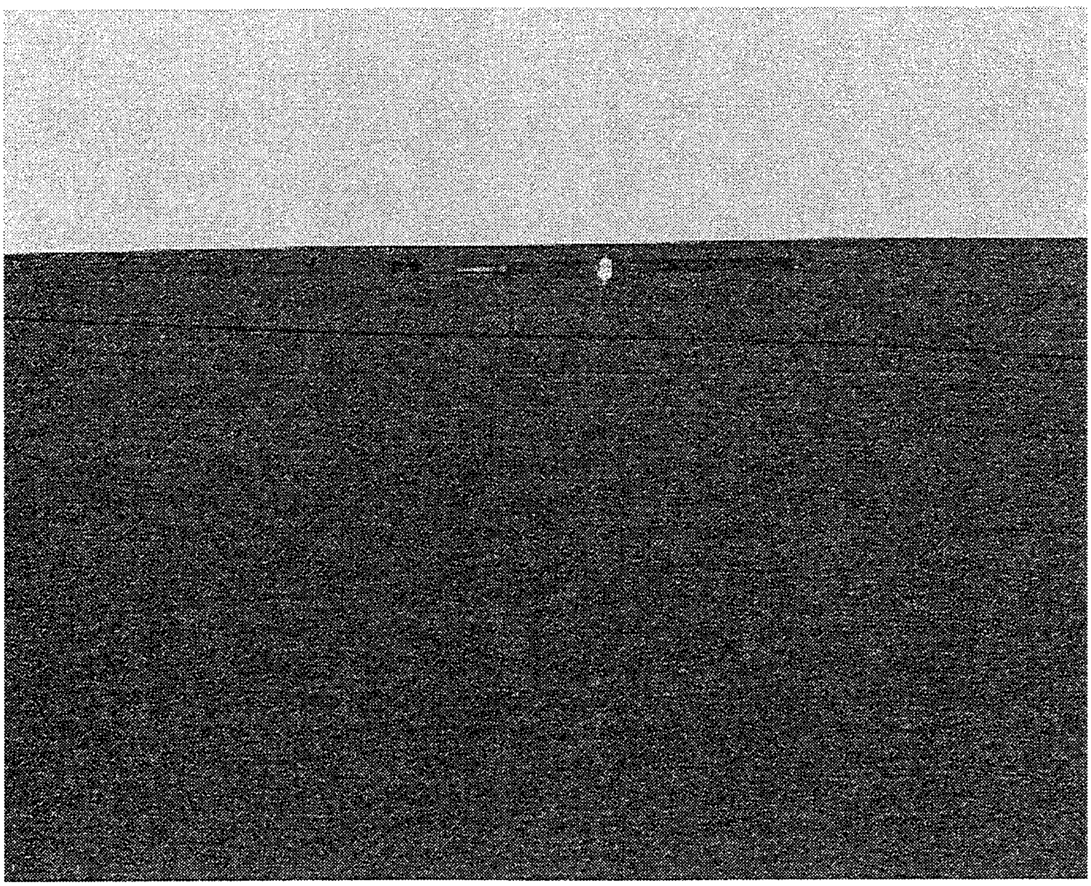


Figure 6. The VMC Sensor/Visibility Condition (VMC)

3.2 Instrument Meteorological Conditions with FLIR Sensor

The computer-generated scene in the IMC with FLIR Sensor Condition resembled the image produced by a FLIR sensor operating in IMC. This condition is referred to as the FLIR Condition and is illustrated in Figure 7. It provided a 35° x 25° field-of-view (FOV) image of the airfield environment that included the various aspects of the visual scene found in VMC (surface texture, runway lights, and surrounding structures). The simulated FLIR sensor image gradually improved as the aircraft proceeded along the precision approach, in such a way that at the Category (CAT) I decision height (200 ft above ground level (AGL)), the sensor image displayed the runway environment with an 1800 ft forward visibility. The FLIR sensor image was displayed throughout the entire approach, including touchdown and rollout.

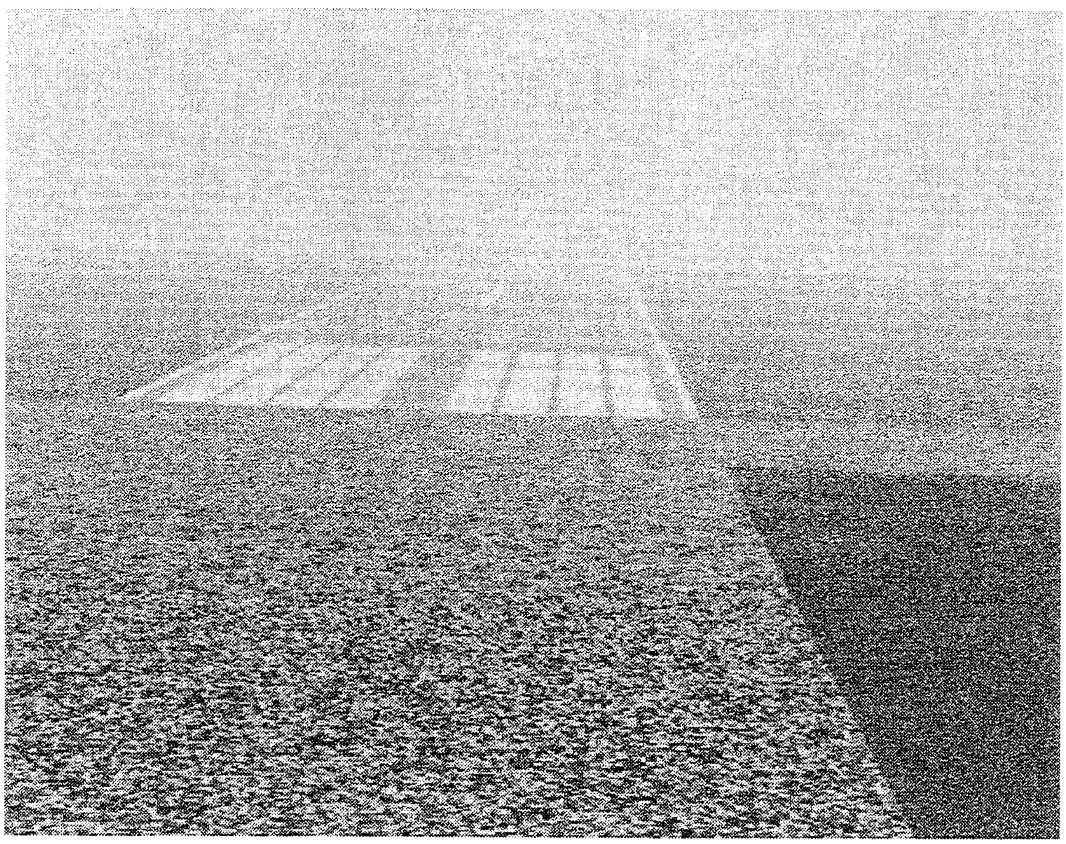


Figure 7. The IMC with FLIR Sensor/Visibility Condition (FLIR)

3.3 Instrument Meteorological Conditions with Millimeter Wave Radar

The OTW view during the IMC with MMWR Condition was a low-fidelity representation of MMWR returns from a series of corner reflectors positioned along the runway edgelines and across the runway threshold. It is therefore referred to as the Corner Reflectors Condition. The image of the runway outline produced by the MMWR returns was discernible at a distance of approximately 1.5 miles from the touchdown zone (see Figure 8).

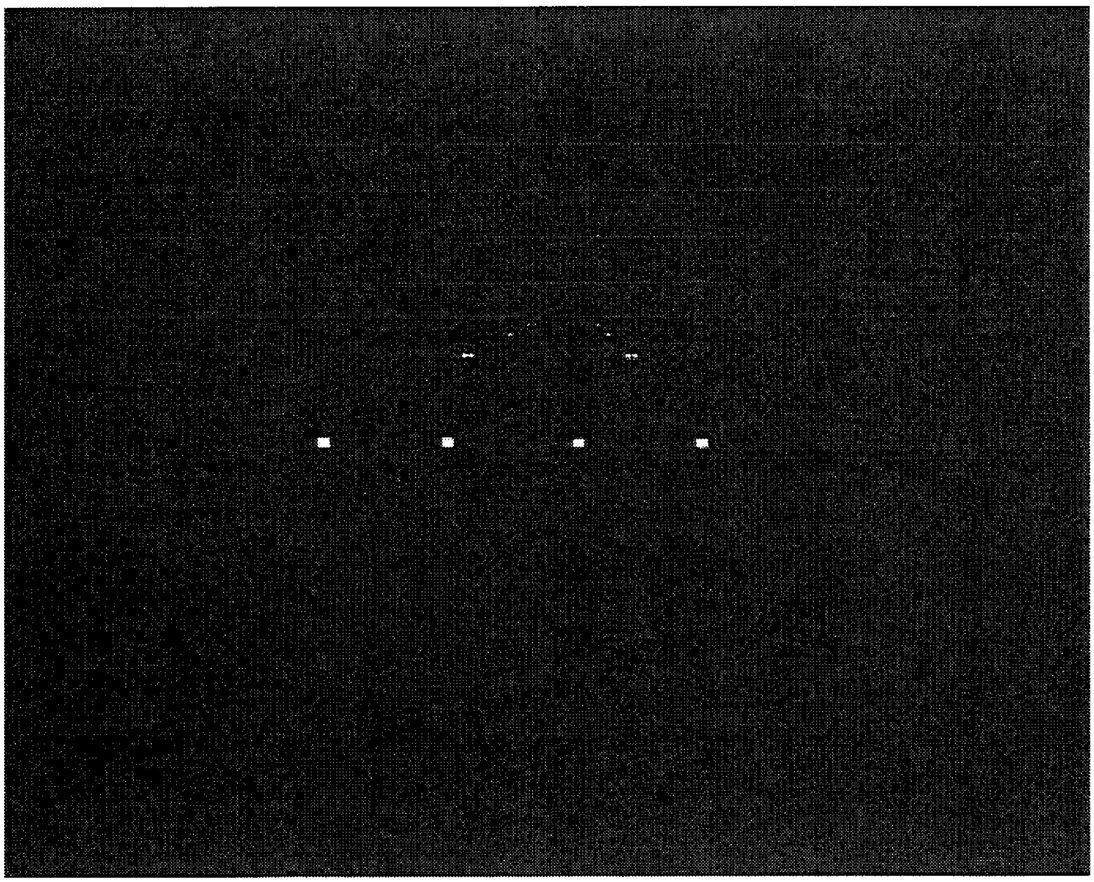


Figure 8. The MMWR Sensor/Visibility Condition (Corner Reflectors)

3.4 No Sensor

The No Sensor Condition was representative of an IMC visibility condition with CAT III weather minimums (0 ft decision height and 700 ft runway visibility range (RVR)). This condition was simulated by incorporating a dense "fog" that obscured the OTW scene to the desired level (see Figure 9).

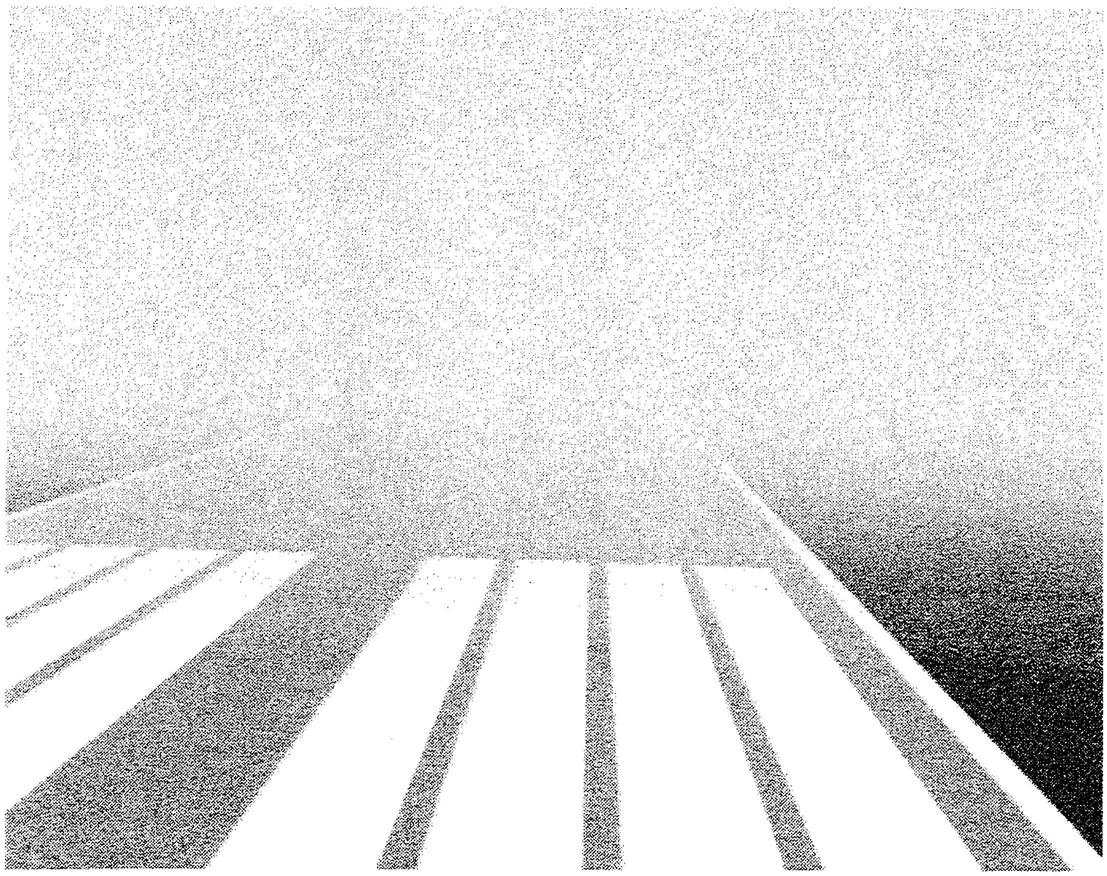


Figure 9. The No Sensor Condition

4. METHODOLOGY

The Autonomous Landing Guidance (ALG) study incorporated a medium-fidelity simulation to address the study objectives that were introduced in Section 1. Twelve pilots performed two experimental tasks in the TRAC simulator: a Precision Approach Task and a Head-Up Display (HUD) Assembly Task. Each pilot participated in a series of training and data collection sessions for the Precision Approach Task and data collection sessions for the HUD Assembly Task. Once the data collection sessions were finished, each pilot completed a Subjective WORkload Dominance (SWORD) form and a set of questionnaires that are described in the following subsections. The use of simulation and the general conduct of the training and data collection sessions are also described below.

4.1 Background and Experience of ALG Pilots

A total of 12 male pilots participated in the ALG study over a period of seven weeks. All but one of the pilots were currently active and most had experience with low-visibility approaches and landings. Nine of the pilots had Air Force transport aircraft experience. Five were Air Force or Air National Guard fighter pilots with HUD experience. Three pilots carried commercial ratings and were actively flying for a passenger airline. The background and experience of the pilots are summarized in Table 2. Abbreviations used in the table are as follows: AC - aircraft commander, IP - instructor pilot, MP - mission pilot, and EP - evaluator pilot.

4.2 The Transport Aircraft Cockpit Simulator

The ALG HUD study was conducted in the Transport Aircraft Cockpit (TRAC) Simulator, which is a reconfigurable full mission simulator with dynamic displays and full flight control capability. Figure 10 provides a representation of the TRAC Simulator. The simulator cockpit approximates a C-141 geometry and contains pilot and co-pilot stations as well as an experimenter's console that is located behind the co-pilot's station. Control yokes

are provided at both pilot stations with the throttle quadrant mounted on the center pedestal. Flight instruments, engine instruments, and other displays are graphically drawn on three large-screen cathode ray tubes (CRTs) mounted in the instrument panel. Other aircraft system controls and displays are installed or mocked-up as required for studies. Two wide-angle collimated (WAC) display windows are mounted directly in front of the pilot and co-pilot stations.

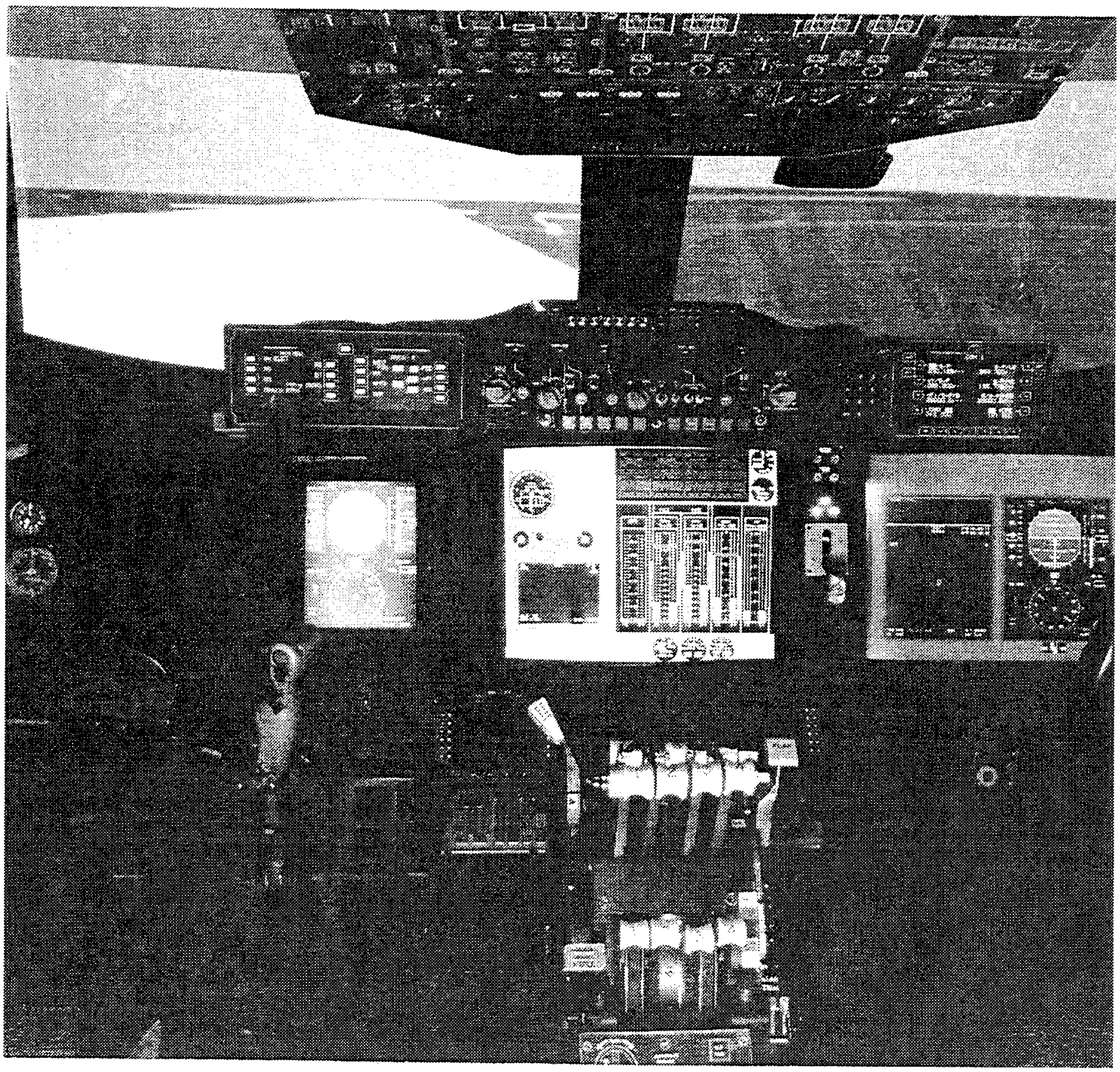


Figure 10. The Transport Aircraft Cockpit (TRAC) Simulator

Table 2. Summary of the Background and Experience of the ALG Pilots

Subject No.	Air Force Transport Rating	Air Force Fighter Rating	Commercial Rating	Total Hours	Low-Visibility Approaches	HUD	Sensors
1	AC			3250	✓		
2	AC	IP		2300		✓	
3	IP			3300	✓		
4		Flight Lead	Captain	7500	✓	✓	
5	IP			2895	✓		
6	AC			2940	✓		
7		MP		705		✓	
8	EP			2950		✓	✓
9	AC		First Officer	2150	✓		
10		EP		2150		✓	
11	EP			7500			✓
12	AC	EP	Captain	5920	✓	✓	

In the conduct of the ALG study, the pilots flew from the pilot's flight station while the co-pilot's station remained unattended. The test engineer sat at the experimenter's console behind the co-pilot's station. The HUD symbology and the out-the-window (OTW) visual scene (one of the four Sensor/Visibility Conditions) were presented on both WAC windows. Graphically drawn engine instruments were provided on the center CRT mounted in the instrument panel. No other head-down flight instruments were provided.

4.3 Training

Each pilot received a classroom briefing regarding the ALG concept, the TRAC simulator, and the HUD symbology dynamics and mechanization. The pilot then participated in a series of simulator familiarization flights, which included practice approaches with each of the 16 combinations of the HUD Symbology Sets and Sensor/Visibility Conditions. The practice approaches were flown using a database fashioned after the Pope Air Force Base (AFB) airfield.

4.4 The Precision Approach Task

In the Precision Approach Task, each pilot flew two replications with each combination of the four HUD Symbology Sets (Basic/RWY, Basic/RAW, Basic/BOTH, and Full HUD) and the four Sensor/Visibility Conditions (VMC, FLIR, Corner Reflectors, and No Sensor), resulting in a total of 32 precision approaches. The approaches were initiated five miles from the touchdown zone, with the aircraft configured for final approach (gear down, flaps set) and established on glideslope and on localizer course. The pilot set the engine throttles to maintain the commanded approach speed and sink rate and manually flew the entire approach to touchdown. A variable quartering headwind was present to elicit active pilot control and to exercise the HUD symbology.

The following objective performance measures were collected at a rate of 30 Hz during the Precision Approach Task: Root-Mean-Square (RMS) glideslope deviation, RMS localizer deviation, RMS airspeed deviation from commanded airspeed, and RMS vertical velocity deviation. As illustrated in Figure 11, the variables were collected for two segments of the approach - "long final" and "short final." In the long final segment, the runway environment was not visible and the pilot used the symbology as the primary flight reference. In the short final segment, the runway environment was either visible or provided via sensor imagery with the pilot having transitioned to the "visual" portion of the approach. The two segments served to identify the relative contribution of sensor imagery and symbology to landing performance and represent the Approach Segment Condition in later sections of this report. The discrete values of touchdown deviation from the centerline and touchdown deviation from the runway point of intercept (RPI) established 1000 ft from the threshold were also collected for each approach and analyzed as objective performance measures.

Figure 11. The Two Data Collection Windows of the Precision Approach Task

4.5 The HUD Assembly Task

Upon completing the Precision Approach Task, each pilot performed the HUD Assembly Task. In this task, each pilot viewed a variety of static Approach Conditions while occupying the pilot station in the TRAC simulator. Each pilot was presented with a total of nine Approach Conditions, each representative of the situations they experienced in the Precision Approach Task. The nine Approach Conditions are shown in Table 3.

Each condition began with the Full HUD Symbology Set displayed. The pilot then verbally selected the HUD symbols he wanted to retain or delete. The test engineer selected or deselected the symbols using the experimenter's console, and the resultant HUD symbology set was displayed in real-time. Once the pilot was satisfied with his selections for a given condition, the selections were saved to a data file. Two HUD symbology sets were constructed: an absolute minimum symbology set and an optimum symbology set. For the minimum symbology set, the pilot was asked to identify the minimum symbology he would require to safely complete an approach. For the optimum symbology set, the pilot was asked to identify the symbology set he believed would result in the best performance.

Table 3. The Approach Conditions for the HUD Assembly Task

Condition	Sensor/Visibility	A/C Orientation	A/C Position
1	VMC	no crab	long final
2	FLIR	crab	long final
3	FLIR	no crab	long final
4	FLIR	crab	short final
5	FLIR	no crab	short final
6	Corner Reflectors	crab	long final
7	Corner Reflectors	no crab	long final
8	Corner Reflectors	crab	short final
9	Corner Reflectors	no crab	short final

4.6 Questionnaires

After completing the HUD Assembly Task, each pilot provided a subjective workload evaluation as well as ratings and comments collected using a questionnaire. The questionnaire is provided in Appendix A. The workload evaluation was accomplished using the SWORD technique (Vidulich, 1989). A SWORD form was used to collect pairwise comparisons of workload across the HUD Symbology Sets. The comparisons were then entered into the SWORD computer program that calculated workload ratings for the HUD Symbology Sets. The questionnaire provided acceptability ratings regarding all aspects of the various HUD Symbology Sets, as well as comments that augmented the acceptability ratings.

4.7 Experimental Design

In the Precision Approach Task, each of the four HUD Symbology Sets were flown in each of the Sensor/Visibility Conditions, resulting in 16 experimental conditions. A repeated measures design was employed, in which two replications of each of the 16 experimental conditions were flown. The presentation order of the experimental conditions was blocked with respect to the Sensor/Visibility Condition, so that each of the four HUD Symbology Sets were flown in a specific Sensor/Visibility Condition before proceeding to the next Sensor/Visibility Condition. The presentation order of the blocked Sensor/Visibility Conditions was counterbalanced across pilots using the Latin Squares technique to reduce the

potential for order effects. Within each Sensor/Visibility block, the presentation order of the HUD Symbology Sets was counterbalanced across pilots, further reducing the potential for order effects.

For the HUD Assembly Task, each pilot received the nine Approach Conditions in the order shown in Table 3. In each case, the "safe minimum" symbology set was identified first, followed by the "optimum" symbology set.

5. RESULTS AND DISCUSSION

This section provides a summary of the data analysis methods, significant Analysis of Variance (ANOVA) results, findings from the questionnaire data, and a discussion of the cumulative results for each analysis objective. The analysis objectives paralleled the study objectives: 1) Determine the relative effects of different symbology sets and their inherent levels of clutter on pilot performance, pilot acceptance, and pilot workload; 2) Determine the effect of sensor imagery on pilot performance, pilot acceptance, and pilot workload in an Autonomous Landing Guidance (ALG) context; and 3) Identify "safe minimum" and "optimum" symbology sets.

5.1 Objective 1

The first objective of the ALG study was to determine the relative effects of different symbology sets and their inherent levels of clutter on pilot performance, pilot acceptance, and pilot workload.

5.1.1 Data Analysis

The analysis for Objective 1 was conducted by assessing pilot performance data, relative workload ratings, and questionnaire responses. Statistical comparisons of the performance levels and workload ratings, using ANOVA techniques, were performed across the different head-up display (HUD) Symbology Sets and within the Sensor/Visibility Conditions, as well as the Approach Segment Conditions. Post-hoc ANOVAs and Duncan tests were performed on the main and interaction effects to identify the nature of the statistical differences. Appendix B provides the F-statistics, significance levels, and means associated with the tested effects. For the questionnaire ratings, experimenters computed frequencies and averages and summarized pilot comments. The ratings and comments supplied by the pilots are summarized in Appendix C.

Table 4 provides a summary of the tested effects that were relevant to this objective and their results. Cells with an $\alpha < .05$ indicate a statistically significant finding. The abbreviations used in the table are as follows: HUD - HUD Symbology Set; VV - vertical velocity; IAS - indicated airspeed; TD - touchdown zone; and CENTER - runway centerline.

Table 4. Analyses Performed for Objective 1

	RMS LOCALIZER	RMS GLIDESLOPE	RMS VV	RMS IAS	ERROR TD	ERROR CENTER
MAIN EFFECTS						
HUD	$\alpha < .05$	$\alpha < .05$	$\alpha < .05$		$\alpha < .05$	
INTERACTION EFFECTS						
HUD X Approach Segment		$\alpha < .05$	$\alpha < .05$	$\alpha < .05$		
HUD X Sensor/Visibility		$\alpha < .05$	$\alpha < .05$	$\alpha < .05$	$\alpha < .05$	
HUD X Segment X Sensor/Visibility		$\alpha < .05$				

5.1.2 ANOVA Results

The following results are based on the ANOVA procedures and post-hoc tests that were applied to the performance and workload data. Basic/RWY, Basic/RAW, Basic/BOTH, and Full HUD refer to the HUD Symbology Sets described in Section 2.

- In all of the of Sensor/Visibility Conditions and in both Approach Segments, the pilots maintained glideslope and localizer most precisely with the Basic/RAW and the Basic/BOTH Symbology Sets, and least precisely with the Basic/RWY set (see Figures 12 and 13). An analysis of the triple interaction involving Approach Segment (Figure 12) revealed a similar pattern for the long and short final approach segments, which differed in magnitude only (see Appendix B). Also, when using the Full HUD, pilots were less precise at staying on the localizer (see Figure 13).

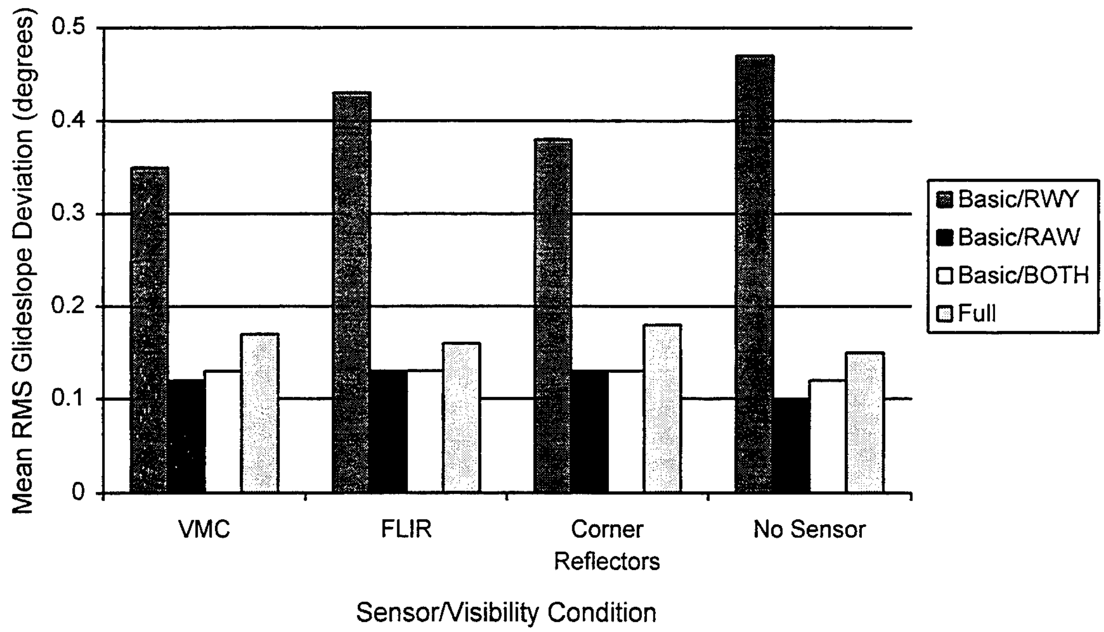


Figure 12. Glideslope Deviation Performance as a Function of Sensor/Visibility Condition and HUD Symbology Set

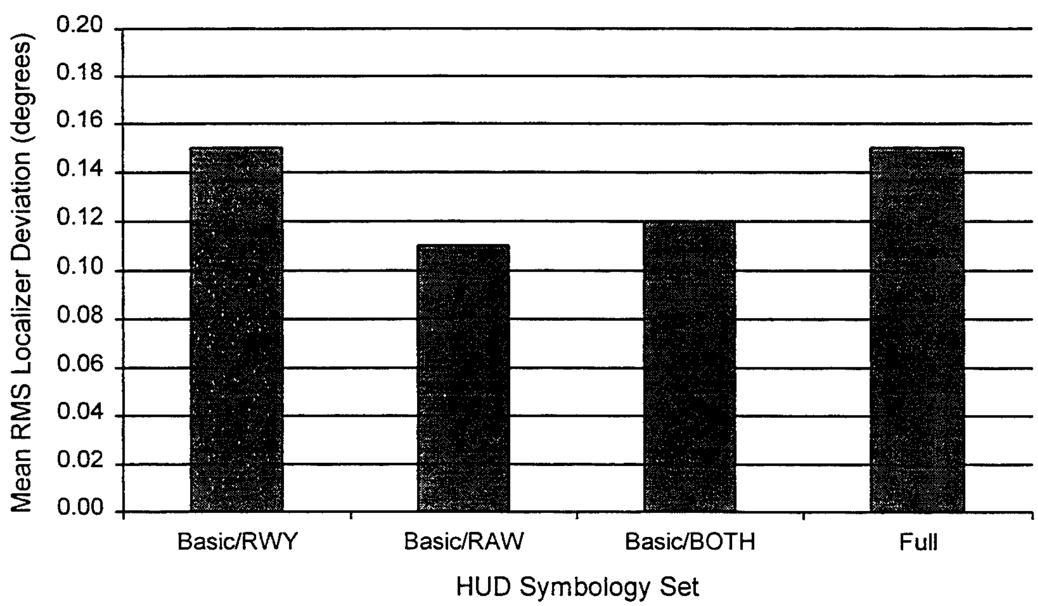


Figure 13. Mean RMS Localizer Deviation as a Function of HUD Symbology Set

- In all Sensor/Visibility Conditions except VMC, pilots most accurately maintained the desired vertical velocity when using the Basic/RWY HUD set.
- Pilots rated workload higher for the Basic/RWY and Full HUD sets than for the Basic/RAW and Basic/BOTH HUD Symbology Sets (see Figure 14).

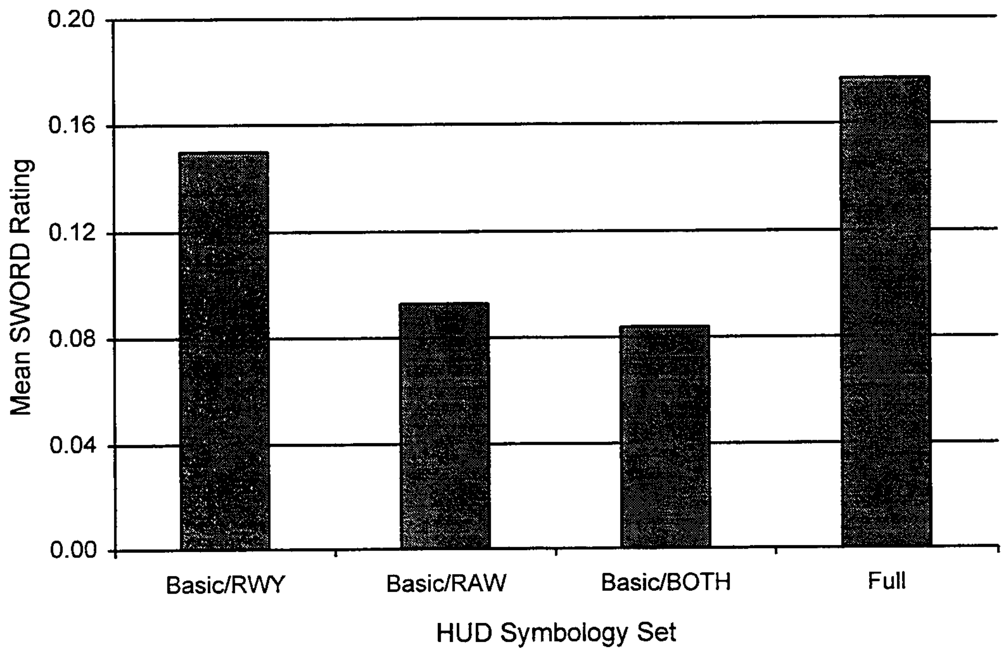


Figure 14. Mean Workload Rating Across Subjects as a Function of HUD Symbology Set

5.1.3 Questionnaire Results

The following results are based on the pilot comments and frequency distributions and averages calculated for the questionnaire rating scales. When asked to rate their ability to accomplish approach tasks (e.g., control lateral deviation, control vertical deviation, control aircraft performance, determine desired touch down point, and safely fly the approach) the pilots most often rated the Basic/RAW and Basic/BOTH formats higher than the Basic/RWY and Full HUD formats (see Figures 15, 16, and 17). For each figure, the rating scale is as

follows: 5 - Very Acceptable; 4 - Moderately Acceptable; 3 - Borderline; 2 - Moderately Unacceptable; 1 - Very Unacceptable. The prevailing pattern for each figure is that the Basic/RAW and Basic/BOTH HUD Symbology Sets received higher acceptability ratings than the Basic/RWY and Full HUDs.

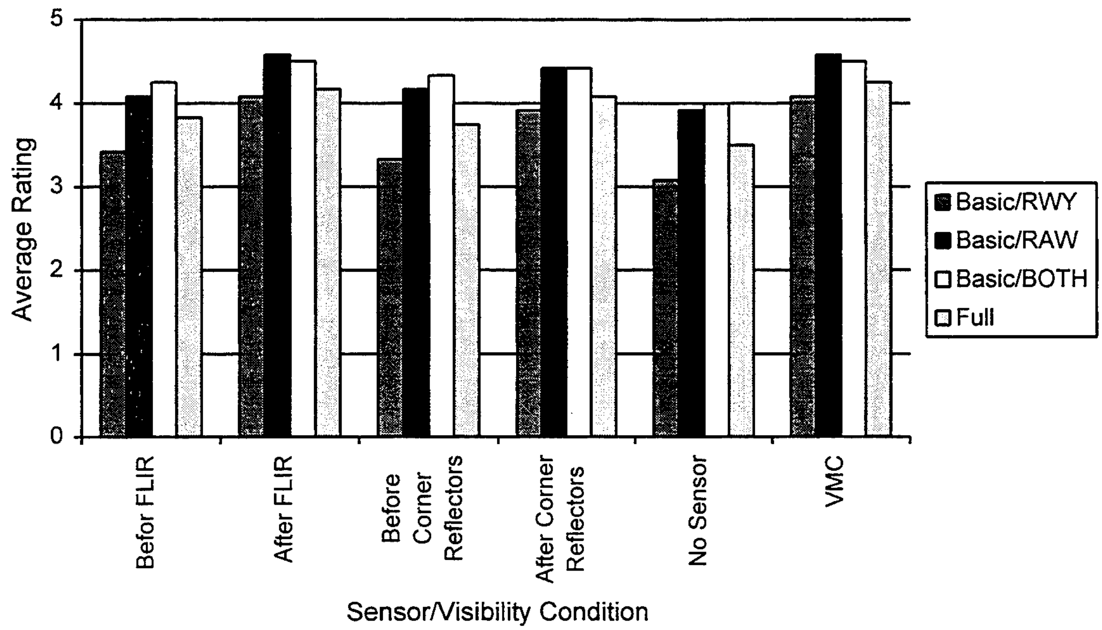


Figure 15. The Average Rating for the Ability to Monitor and *__Control Lateral Deviation__* *as a Function of Sensor/Visibility Condition and HUD Symbology Set*

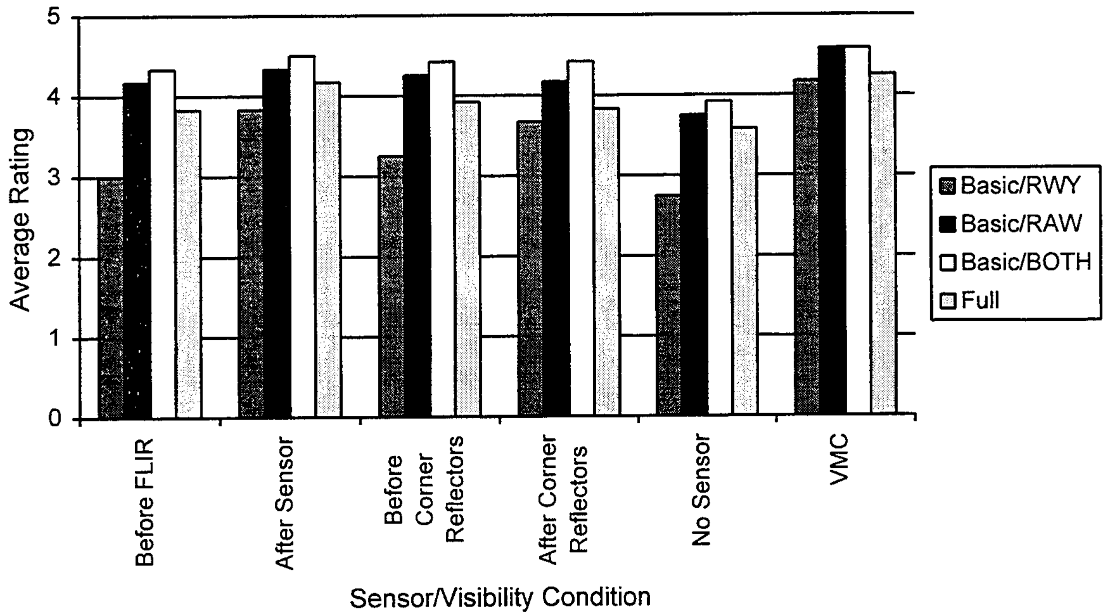


Figure 16. The Average Rating for the Ability to Monitor and Control Vertical Deviation as a Function of Sensor/Visibility Condition and HUD Symbology Set

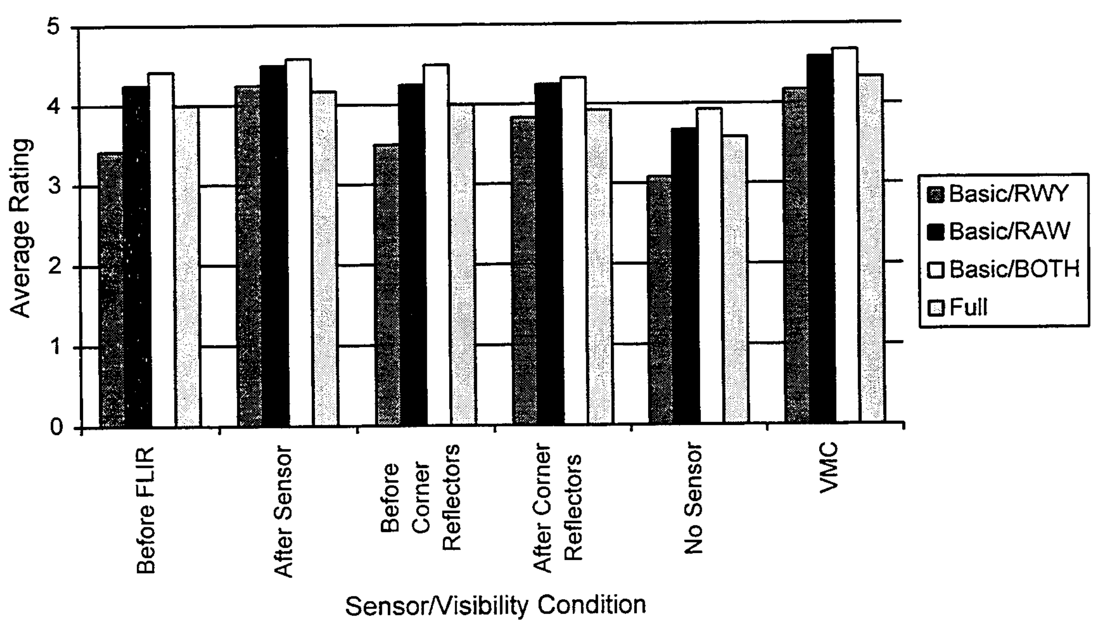


Figure 17. The Average Rating for the Ability to Safely Fly the Approach as a Function of Sensor/Visibility Condition and HUD Symbology Set

Figure 18 illustrates that the pilots reported more safety issues associated with the Basic/RWY HUD and Full HUD than for the Basic/RAW HUD and Basic/BOTH HUD. The figure also shows that the majority of pilots expressed safety concerns with using the Basic/RWY HUD for low-visibility approaches because it did not provide sufficient approach guidance information. Specifically, pilots indicated that raw vertical and lateral deviation data, a course indication, distance measuring equipment (DME), and surface wind direction and magnitude were needed as part of the Basic/RWY set. Pilot recommendations were particularly salient for the long Approach Segment where a sensor or visual image was not available.

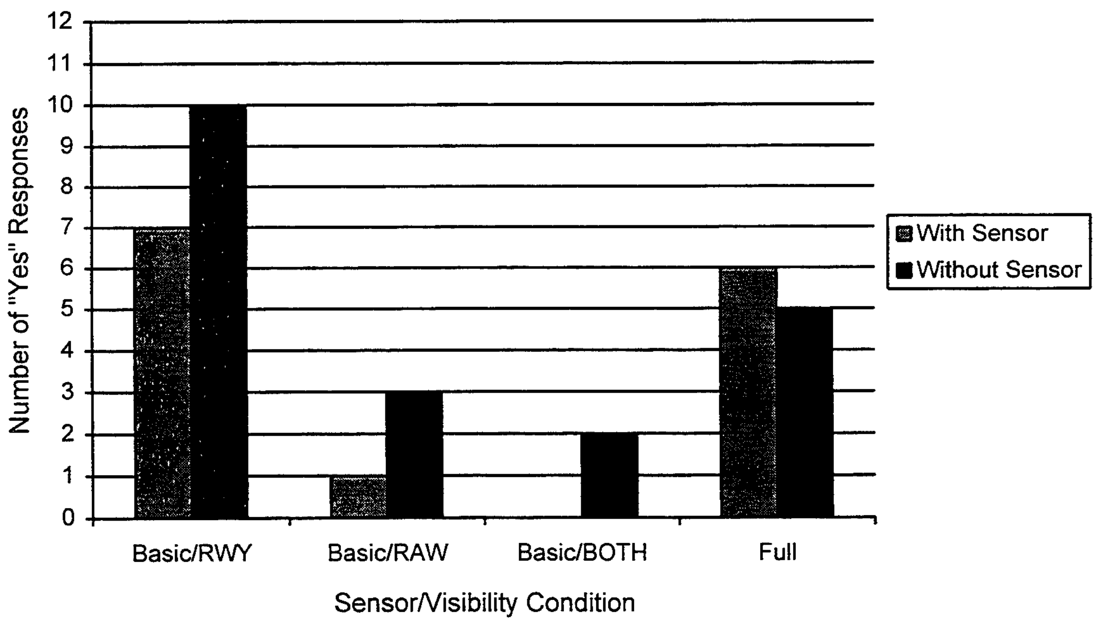


Figure 18. The Number of Pilots that Responded "Yes" to the Question of Safety Issues as a Function of HUD Symbology Set and Sensor Availability

Also, half of the pilots identified safety concerns with the Full HUD set (see Figure 18). Safety issues resulted from the HUD format containing too much information and being too cluttered. Pilots commented that the high information density and resultant clutter was

distracting and obscured the visual scene and important symbology. Comments indicated that the flare and ground annunciators, as well as the rising runway, speed deviation cue, acceleration cue, and artificial runways were largely unnecessary. Conversely, the pilots expressed very few safety concerns with the Basic RAW and Basic/BOTH sets.

The HUD Symbology Sets suffered clutter problems in varying degrees (see Figure 19). The Basic/RWY and the Basic/RAW HUDs had the least clutter problems, while the Full HUD suffered the most because of clutter. The pilots consistently commented that the aircraft reference symbol (part of the Basic HUD set) was too large and provided information of dubious utility.

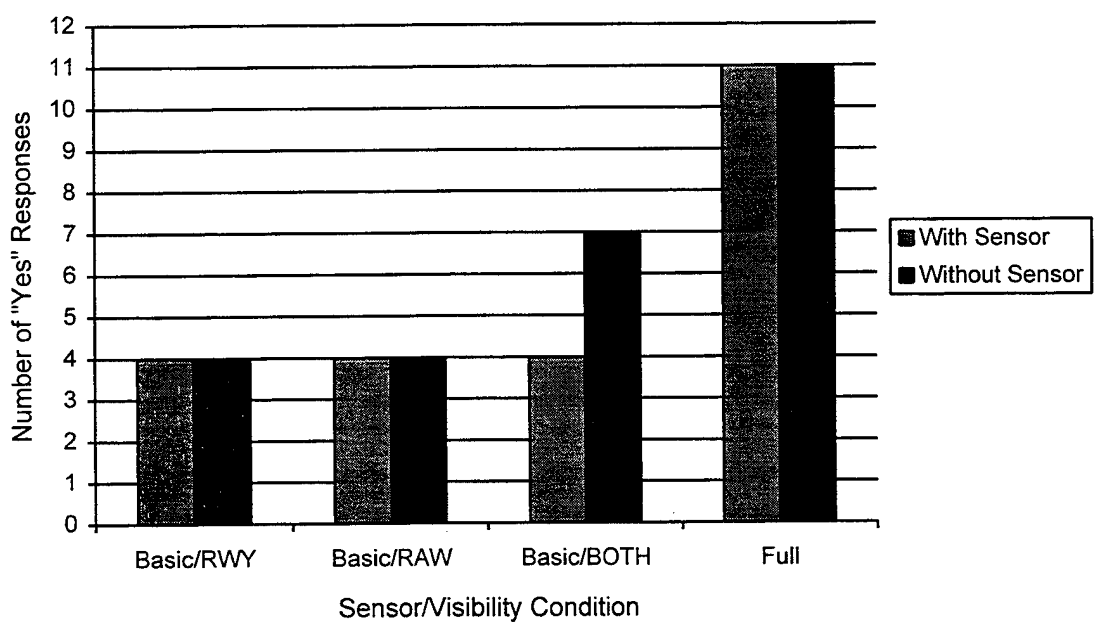


Figure 19. The Number of Pilots that Responded "Yes" to the Question of Clutter Issues as a Function of HUD Symbology Set and Sensor Availability

5.1.4 Objective 1 Discussion

The performance and workload results show a consistent pattern as a function of the HUD Symbology Sets. The pilots performed better and rated workload lower with both the

Basic/RAW and Basic/BOTH Symbology Sets than with the Basic/RWY and Full HUD Symbology Sets. Responses to questionnaire items showed the same pattern, indicating the Basic/RWY format did not provide adequate information, and the Full HUD format contained too much information.

The findings suggest that a continuum of symbology density (and resultant clutter) exists, with a minimum symbology density (or information density) at one end and a maximum symbology density at the other. As expected, the Precision Approach Task performance data suggest that a minimum amount of symbology (information) must be provided to obtain acceptable levels of performance. Adding symbology (information) can improve performance until a point on the continuum is reached; thereafter, excessive clutter begins to degrade performance. In reference to the performance data from the Precision Approach Task, and the workload and questionnaire data, the minimum symbology provision should include more information than is available with the Basic/RWY HUD set, and less than is available with the Full HUD.

5.2 Objective 2

The second objective of the ALG study was to determine the effect of sensor imagery on pilot performance, pilot acceptance, and pilot workload in an ALG context.

5.2.1 Data Analysis

As with Objective 1, the analyses for the Objective 2 involved the assessment of the pilot performance data, relative workload ratings, and questionnaire responses. The Precision Approach performance data and the workload ratings were investigated using ANOVA techniques as a function of the HUD Symbology Sets and within the Sensor/Visibility Conditions. Post-hoc ANOVAs and Duncan tests were performed on the main and interaction effects to identify the nature of the statistical differences. Appendix B provides the F-statistics, significance levels and means associated with all of the tested effects. Frequencies and averages were computed for the questionnaire ratings and the pilot comments were

summarized. Table 5 provides a summary of the tested effects that were relevant to this objective and their results. Cells with an $\alpha < .05$ indicate a statistically significant result. The abbreviations used in the table are as follows: HUD - HUD Symbology Set; VV - vertical velocity; IAS - indicated airspeed; TD - touchdown zone; and CENTER - runway centerline.

Table 5. Results of the ANOVAs Accomplished for Each Performance Variable as a Function of Sensor/Visibility Condition

	RMS LOCALIZER	RMS GLIDESLOPE	RMS VV	RMS IAS	ERROR TD	ERROR CENTER
MAIN EFFECTS						
Sensor/Visibility				$\alpha < .05$		$\alpha < .05$
INTERACTION EFFECTS						
HUD X Sensor/Visibility		$\alpha < .05$	$\alpha < .05$	$\alpha < .05$		

5.2.2 ANOVA Results

The following results are based on the ANOVA procedures and post-hoc tests that were applied to the performance data. A detailed treatment of the main and interaction effects may be found in Appendix B. The results of the workload analysis are not reported because no significant differences were found as a function of Sensor/Visibility Conditions:

- Pilots touched-down closer to the runway centerline in the VMC and FLIR Conditions than in the Corner Reflector and No Sensor Conditions (see Figure 20).

- The interactions between HUD Symbology Set and Sensor/Visibility Condition were examined, but produced only one interesting finding. With the Full HUD Symbology Set, the pilots flew glideslope most accurately in the VMC Condition and least accurately in the FLIR and No Sensor Conditions.

- With the Basic/RAW Symbology Set, the pilots maintained airspeed and vertical velocity most precisely in the VMC Condition and least precisely with the No Sensor Condition.

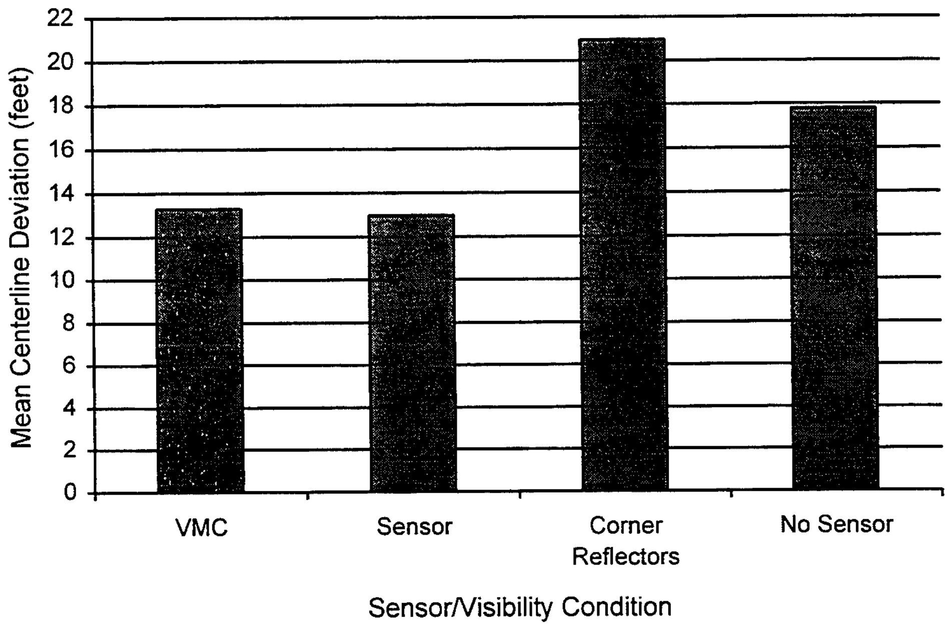


Figure 20. Mean Touchdown Deviation from Centerline as a Function of Sensor/Visibility Condition

5.2.3 Questionnaire Results

Pilots consistently rated their ability to accomplish the approach tasks as between "Moderately Acceptable" and "Borderline" when flying in the No Sensor Condition (see Figures 15, 16, and 17). This trend may have been influenced by the low contrast between the symbology and the dense white "fog" background in the No Sensor Condition. The pilots also consistently rated their ability to safely perform the approach (and specific approach tasks) as very low (e.g., below moderately acceptable) when using the Basic/RWY HUD before the sensor image became visible. Average pilot ratings on the ability to accomplish approach tasks did not appear to depend on the Sensor/Visibility Conditions for the other three HUD Symbology Sets. Overall, pilots were very positive about the benefits of the sensor imagery

for low-visibility approaches. When asked about the viability of the ALG concept, the pilots expressed high confidence in both the concept and the resulting integration of symbology and sensor imagery on a HUD display.

5.2.4 Objective 2 Discussion

As expected, both performance and subjective data showed performance benefits as a result of adding sensor imagery of the runway environment. However, the Sensor/Visibility Conditions did not affect pilot workload ratings. The pilots performed the same in the FLIR and VMC Conditions. The subjective data also indicated that the perceived benefits of the sensor imagery were greater when the HUD symbology provided limited information. The relatively low-quality sensor image provided in the Corner Reflector Condition did not improve performance over the No Sensor Condition. This may have resulted from the low-fidelity representation of MMWR or from the absence of visual cues such as texture, surface features, or ground objects. However, these findings emphasize the importance of a high quality sensor imagery in ALG applications.

5.3 Objective 3

The third objective of the ALG study was to identify "safe minimum" and "optimum" ALG HUD symbology sets.

5.3.1 Data Analysis

Objective 3 was directly addressed by evaluating the HUD Assembly Task data. However, much of the pilot performance and questionnaire data addressing clutter is also relevant to this objective. A frequency analysis was performed on the HUD Assembly Task selections to identify how many pilots selected each possible symbol for each Approach Condition.

5.3.2 Frequency Analysis Results

Table 6 shows the results of the frequency analysis performed on the HUD Assembly Task data. Safe minimum and optimum selections are shown in columns for each Approach Condition. Each row represents a HUD symbol. An "X" indicates that at least half of the pilots selected the symbol for the Approach Condition represented in that column. In the far left column, a "B" indicates the symbol was provided as part of the Basic HUD symbol set, an "A" indicates approach symbology, and an "F" indicates the symbols were included in the Full HUD. On the top row, CR indicates Corner Reflectors.

The following observations are based on an inspection of the frequency analysis results:

- The minimum or optimum symbology sets did not appear to depend on the type of sensor provided or whether a crab condition existed.
- The minimum and optimum symbology sets did appear to differ between short and long final conditions.
- The pilots selected most of the Basic HUD symbology (except the digital groundspeed symbol, the aircraft reference symbol, the digital radar altimeter provision, and the roll limit symbology) for display in all of the Approach Conditions.
- The majority of pilots preferred the raw localizer and glideslope deviation symbology over the artificial runway symbol for executing the approaches.

Two of the symbols from the Full HUD set (digital DME and the surface wind vector) were selected for inclusion in the preferred sets. The pilots also selected two mode-dependent symbologies for long final conditions: the course deviation indicator (CDI) needle and the to-from indicator.

Table 6. Results of the HUD Assembly Task Frequency Analysis

	Trial Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Sensor/Visibility	VMC	VMC	FLIR	FLIR	FLIR	FLIR	FLIR	FLIR	FLIR	FLIR	CR	CR	CR	CR	CR	CR	CR
	Approach Orientation	No Crab	No Crab	Crab	Crab	No Crab	No Crab	Crab	Crab	No Crab	No Crab	Crab	Crab	No Crab	No Crab	Crab	Crab	No Crab
	Approach Segment	Long Final	Long Final	Long Final	Long Final	Long Final	Long Final	Short Final	Short Final	Short Final	Short Final	Long Final	Long Final	Long Final	Long Final	Short Final	Short Final	Short Final
	Symbology Set	Minimum	Optimum	Minimum	Optimum	Minimum	Optimum	Minimum	Optimum	Minimum	Optimum	Minimum	Optimum	Minimum	Optimum	Minimum	Optimum	Minimum
B	Flight Path Marker	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Vertical Scale	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Horizon Line	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Heading Scale	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Digital Heading	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Actual Heading Marker	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Actual Track Marker	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Actual Digital Airspeed	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Digital Barometric Altitude	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Roll Scale	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	AOA Limit	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Selected Heading Marker		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Digital Vertical Speed		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Yaw Indication		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
B	Selected Vertical Reference		X	X	X	X	X		X	X	X	X	X	X	X	X	X	
B	Digital Groundspeed		X		X		X		X		X		X		X		X	
B	Digital Radar Altimeter							X	X	X	X					X	X	X
B	Roll Limits							X	X	X	X					X	X	X
A	Raw Localizer		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
A	Raw Glideslope		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
A	Selected Course			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
A	Artificial Runway								X		X		X		X	X	X	X
F	DME		X	X	X	X	X		X		X	X	X	X	X		X	
F	To-From Indication	X	X	X	X	X	X					X	X	X	X			
F	CDI Needle	X	X	X	X	X	X					X	X	X	X			
F	Wind Vector		X		X		X		X		X		X		X		X	
F	Rising Runway								X		X						X	
F	Flightpath Guidance Cue				X		X						X					
F	AC Reference																	
F	Speed Worm																	
F	Acceleration Cue																	
F	Landing Advisory																	
F	Flare Annunciator																	

Table 7 summarizes the pilots' selections for minimum and optimal symbology sets. Based on the frequency analysis that was performed on the HUD Assembly Task data (see Table 6), separate symbology sets are recommended for the short and long final approach segments. Note also that nearly all of the symbols were retained throughout the entire approach, suggesting that the sensor image was used as supplementary information, rather than as a replacement for selected symbology. The retention of symbology is due in part to the range limitations of the sensors modeled in this study (and sensors in general). The recommended minimum and optimum symbology sets for each Approach Segment are represented in Figures 21, 22, 23, and 24.

Table 7. HUD Symbology Recommendations as a Function of Approach Segment

	Long Final	**Short Final**
Minimum Symbol Set	Basic + Raw *minus* Aircraft Reference Digital Groundspeed *plus* Selected Course DME "CDI needle"	Basic + Raw *minus* Aircraft Reference Digital Groundspeed *plus* Selected Course DME
Optimum Symbol Set	Basic + Raw *minus* Aircraft Reference Digital Groundspeed *plus* Selected Course DME "CDI Needle" Wind Vector Flight Path Guidance Cue	Basic + Raw *minus* Aircraft Reference Digital Groundspeed *plus* Selected Course DME Wind Vector Flight Path Guidance Cue Artificial Runway Rising Runway

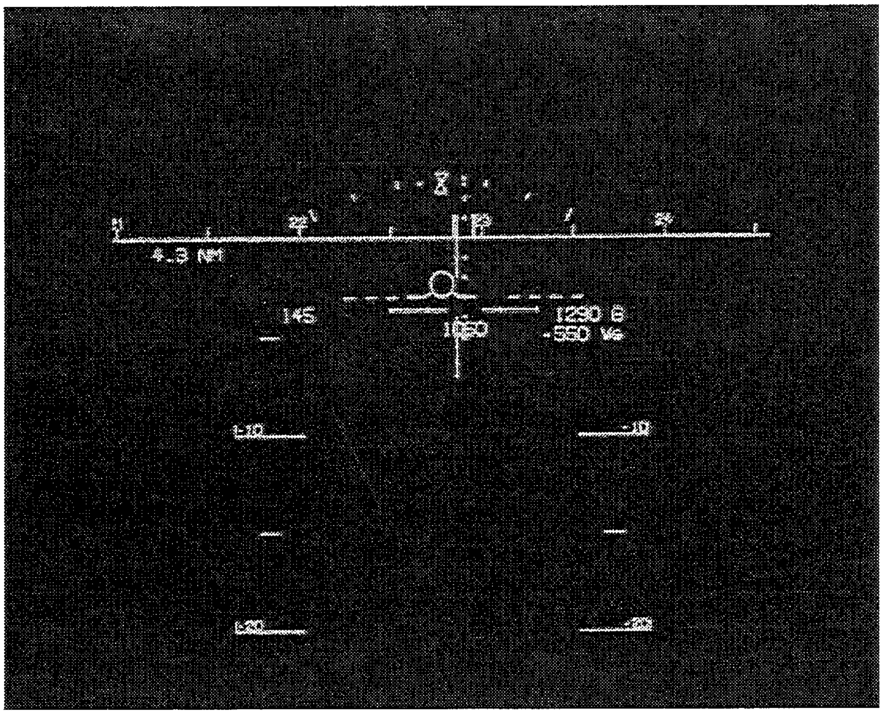


Figure 21. The Recommended Minimum Symbology for Short Final

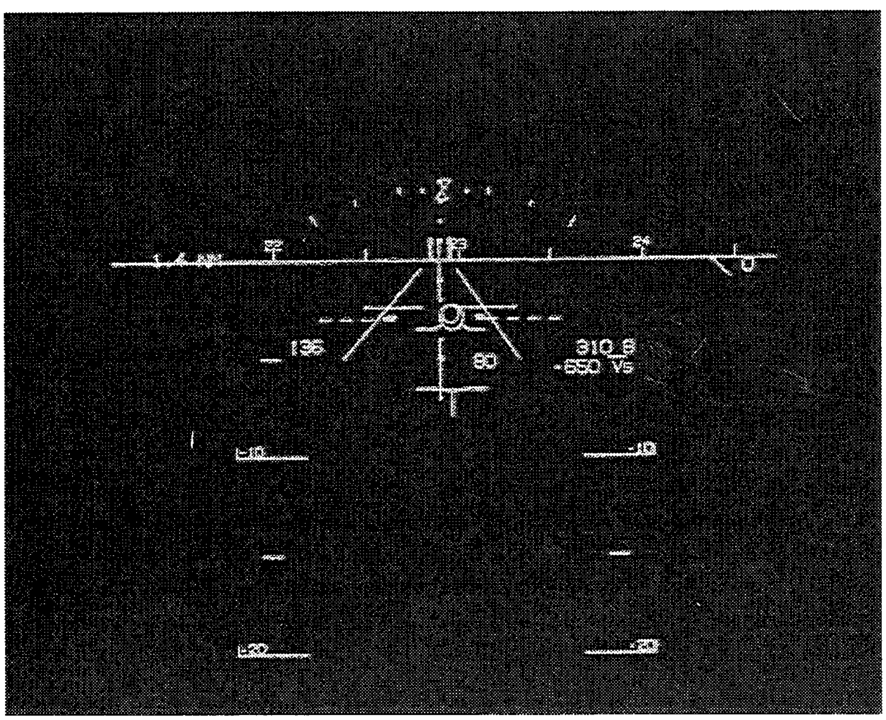


Figure 22. The Recommended Maximum Symbology for Short Final

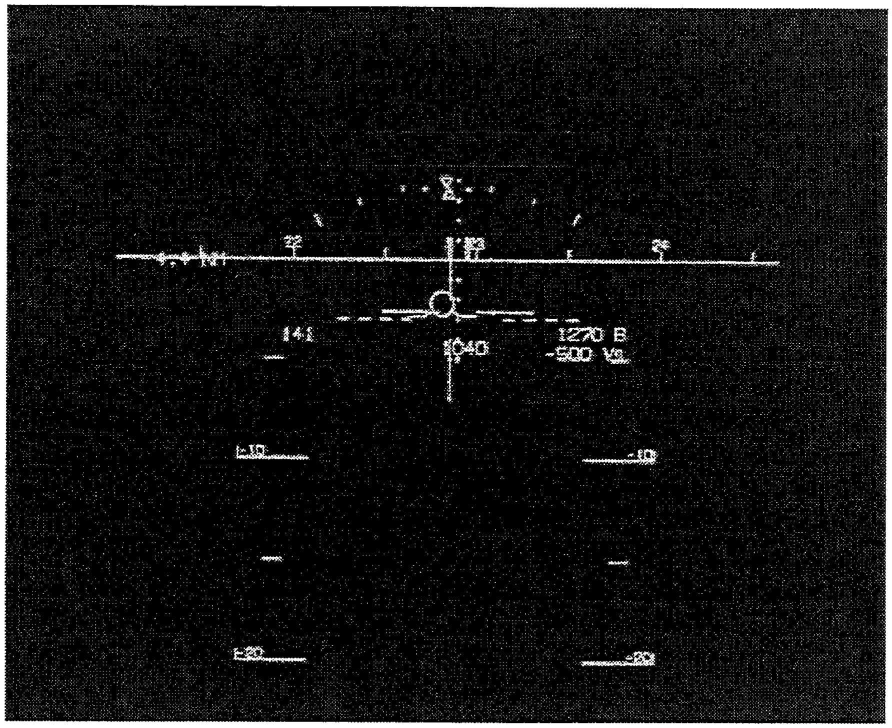


Figure 23. The Recommended Minimum Symbology Set for Long Final

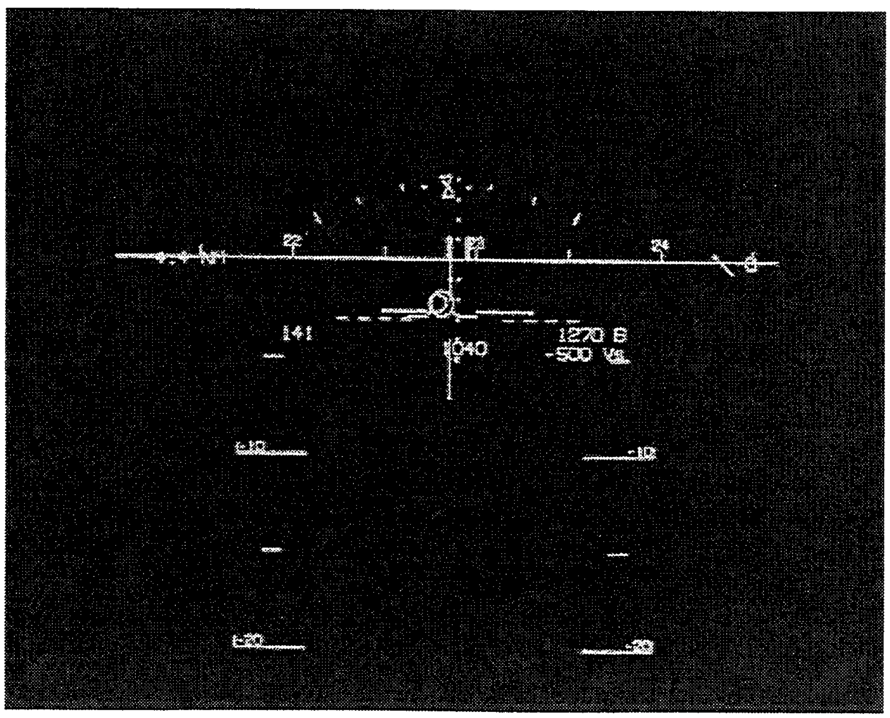


Figure 24. The Recommened Maximum Symbology Set for Long Final

5.3.3 Objective 3 Discussion

The performance, workload, and questionnaire results along with the frequency analysis results provide converging evidence that an optimum HUD symbology set for ALG applications contains more symbology than is provided in the Basic/RWY Symbology Set and less symbology than is found in the Full HUD. The performance data identifies the Basic/RWY HUD as possibly being below the "safe minimum" and certainly not "optimum" from a performance standpoint. The clutter problems identified by the pilots would also eliminate the Full HUD from consideration as the "optimum" symbology set. Due to the excessive workload and the associated questionnaire comments, this research strongly suggests that the artificial runway is inadequate as a guidance symbology and should not be considered for either the "minimum safe" or "optimum" symbology set. Conversely, because the raw data tended to reduce workload, both the raw localizer deviation and the raw glideslope deviation should be strongly considered for inclusion.

5.4 General Discussion

Recall that the current study is intended to lead to HUD symbology requirements for an ALG system. To that end, the results of the current study provide a recommended symbology set for ALG applications that is supported by pilot performance and pilot subjective data. With few exceptions, the current recommendations for approach symbology are consistent with previously published HUD information requirements and recommendations, such as MIL-STD-1787, Weintraub and Ensing (1992), Ercoline and Weinstein (1993), and Hughes, et al. (1992).

The single inconsistency between the results of this study and most HUDs currently in the field is the presentation of energy management cues (longitudinal acceleration and angle-of-attack (AOA)/airspeed deviation). Less than half of the pilots participating in this study selected these cues for inclusion in either the "minimum safe" or "optimum" sets, yet they *are* provided in most fielded HUDs. The lack of pilot familiarity with the operation of these

symbols may account for the inconsistency. Most of the pilots in the evaluation were transport pilots with little or no HUD experience, and therefore had no previous experience with energy management cues. Participation in the study may not have provided sufficient familiarity with the cues because each approach flown in the Precision Approach Task began with the simulator stabilized on localizer and glideslope with the flaps and throttles already correctly set. These relatively stable conditions did not heavily exercise the energy management symbology. If the pilots did not use and understand the symbols, they could not recognize their value.

Even though the current results reflect a high degree of consistency with previous HUD development work, some issues should be considered when generalizing these results. First, the design and information elements provided to the pilots were obviously inseparable and the results presented are based entirely on the Sextant design. In some cases, the design or dynamics of a symbol (e.g., size of the aircraft reference symbol) appeared to have influenced the study results, such as by unnecessarily cluttering the display or causing confusion. Therefore, a different symbology set could have produced slightly different results. Second, the low fidelity of the sensor should also be considered when generalizing results. Specifically, the Corner Reflector Condition was an oversimplified representation of MMWR sensor imagery. In the study, the corner reflectors were shown as dots of white over a black background. The scene did not show any "noise" or returns from other ground objects. The use of the information provided by the corner reflectors may have been better or worse in a more realistic scene. Finally, as in any simulation, the results obtained should not be used to predict real-world pilot performance or workload. However, a similar pattern of results would be expected for real-world conditions.

6. CONCLUSIONS AND RECOMMENDATIONS

The conclusions drawn from this evaluation are directly related to the original objectives of this study: 1) Determine the relative effects of different symbology sets and their inherent levels of clutter on pilot performance; 2) Determine the effect of sensor imagery on pilot performance in an Autonomous Landing Guidance (ALG) task; and, 3) Identify "safe minimum" and "optimum" symbology sets.

A number of conclusions can be drawn regarding the comparison of the different head-up display (HUD) Symbology Sets and their inherent levels of clutter. First, the Basic Symbology Set, with the exception of the aircraft reference symbol, provides a good foundation to build on. Adding the raw data to this set is preferred over the addition of the runway symbol, with virtually no dividend derived from adding both. Finally, this research determined that the Full HUD set provided too much information, at least for those pilots with a limited amount of HUD experience.

In terms of identifying a "safe minimum" symbology set and an "optimum" symbology set, this research indicated that these sets were conditional; that is, the two symbology sets were primarily influenced by the relative distance from the airstrip. The two conditions of distance to the airstrip investigated have been referred to as "long final" (distance measuring equipment (DME) greater than approximately 1.5 Nm) and "short final" (DME less than approximately 1.5 Nm). This differentiation is a direct result of the provision of the sensor image, which can begin to provide information at approximately 1.5 DME. Each set should include, as a minimum, the Basic Symbology Set minus the aircraft reference symbol and the digital groundspeed. The symbols added to the Basic Symbology Set to arrive at the "safe minimum" and "optimum" sets were provided in Table 7 in Section 5, as a function of Approach Segment ("long final" versus "short final").

Because the current study evaluated a single symbology mechanization (Sextant's symbology design) and employed low fidelity sensor imagery, the researchers would be

presumptuous to present these recommendations as the standard for all ALG HUDs. Rather, these recommendations are intended to serve as a guide, allowing for deviations as particular instances warrant. Recalling the continuum of symbology availability, with no symbology at one end and the Full HUD Symbology Set at the other, the recommendations found in Table 7 in Section 5, represent a functional set of symbols for use in a small variety of ALG precision approach conditions. Additionally, the differentiation between the "optimum" and "minimum" symbology sets could serve as a guide for a declutter application, with the "optimum" set being provided as the default and the "minimum" set available as a pilot-selectable declutter option.

Concerning the effect of the addition of sensor imagery, the researchers have concluded from the analyses that the addition of a sensor image (like a forward-looking infrared (FLIR) sensor image) will elicit performance similar to that found in Visual Meteorological Conditions (VMC). Unfortunately, this conclusion could not be extended to the Corner Reflectors Conditions. The researchers believe that this image suffered from a lack of fidelity, as it was a very crude approximation of a millimeter wave radar (MMWR) return from an airfield equipped with corner reflectors. The Corner Reflectors Conditions did not include any other returns from the airfield environment and therefore lacked the peripheral cueing that was available with the FLIR sensor image. The researchers have concluded, however, that an acceptable level of performance could be accomplished with a variety of sensor images (e.g., MMWR, low-light TV), provided they are of nominal quality and serve to extend the "visual" portion of an ALG approach.

As follow-up to this study, several follow-on activities are recommended. The symbology provisions should be evaluated using higher fidelity sensor models; if possible, using actual FLIR or MMWR images rather than simulated versions of the same. Also, we recommend that this evaluation be performed with the sensor imagery and symbology presented on actual HUD hardware mounted in the simulator, as opposed to projecting the HUD symbology on a single display medium (the wide-angle collimated (WAC) windows) with the sensor/visibility scene. Performing a study in this fashion would tend to eliminate

some of the artificiality and limitations associated with the current simulation. Finally, suggestions are to replicate this evaluation with other HUD symbology sets, most notably the MIL-STD HUD. This replication would verify that the *information* necessary in an ALG context remains the same regardless of the particular symbology mechanization incorporated.

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APPENDIX A - QUESTIONNAIRE

Introduction

The questionnaire used in the Head-Up Display (HUD) Symbology Evaluation for the Autonomous Landing Guidance (ALG) System is provided in this Appendix. A summary of the pilots' responses is provided in Appendix C. The questionnaire was used to ellicit the following information from the 12 pilots that participated in the study:

- Biographical data
- An evaluation of the Basic Plus Runway Symbology Set
- An evaluation of the Basic Plus Raw Deviation Data Symbology Set
- An evaluation of the Basic Plus Both Runway and Raw Deviation Data Symbology Set
- An evaluation of the Full Sextant HUD
- General information concerning the TRAC simulator, the ALG concept, and the ALG study as conducted by this laboratory

ALG SYSTEMS QUESTIONNAIRE

The following questionnaire will investigate the utility of each of the four HUD configurations presented in this Autonomous Landing Guidance (ALG) study. Each display will be treated separately. Space has been provided for additional comments after many of the questions. If you need more space, please continue on the back of the page. Any opinions and ideas you may have regarding the improvement of the displays' operational utility and reduction of crew workload will be greatly appreciated.

Name ____________________________

Subject Number ____________________

BIOGRAPHICAL DATA

Grade: 0-1 0-2 0-3 0-4 0-5 0-6

Aeronautical Rating:

Transports:	Fighters:	Commercial:
First Pilot	Pilot	First Officer
Aircraft Commander	Element Lead	Captain
Instructor Pilot	Flight Lead	Check Airman
Evaluator Pilot	Instructor Pilot	
Other (Please specify)	Evaluator Pilot	

Please list the aircraft flown and the approximate number of hours in each, beginning with the most recent.

Aircraft:	Hours:
____________________	____________________
____________________	____________________
____________________	____________________
____________________	____________________
____________________	____________________

Grand Total: ____________________

Indicate your experience level with the following:

a) Precision approaches in low visibility conditions
   Transport pilots: Weather certification (CAT II, CAT III) ____________
   Fighter pilots: Pilot weather category (ceiling/visibility) ____________
b) HUD instrument approaches (none, a few, several, etc.) ____________
c) Approximate number of hours flown with electro-optical sensors such as IR, radar, low light TV, etc. ____________

Organization:____

Duty Station:__________________________________Duty Phone:__________________

May we contact you if additional information is needed? ________

Time Since Last Flight: Months/Days _________

The Full HUD Design

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Full HUD** in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E). The first table applies to the approach segment *before* the sensor image was available. The second table applies to the approach segment *after* the sensor image was available.

Acceptability Scale

A. **Very acceptable:** All information readily available and easily interpreted.
B. **Moderately acceptable:** All information available and interpretable; minor issues having no impact on pilot performance.
C. **Borderline:** Incomplete information and/or troublesome interpretation; changes would be desirable.
D. **Moderately unacceptable:** Lack of information and/or difficult interpretations impair pilot performance; corrections required.
E. **Very unacceptable:** Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

1. *Before* the sensor image/visual scene was available:	OTW Condition: With Sensor	Corner Reflectors	No Sensor
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			

Comments:

2. After the sensor image/visual scene was available:	OTW Condition VMC	With Sensor	Corner Reflectors
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			
g) Determine desired touchdown point			

Comments:

3. Use the above Acceptability Scale to rate the overall acceptability of the Full HUD. _____

4. Use the Modified Cooper Harper Scale (last page of this package) to rate the workload associated with the Full HUD in each of the following conditions:

   a. VMC _____

   b. With a sensor image _____

   c. With the corner reflectors _____

   d. Without a sensor image _____

5. Did you experience any clutter problems with the Full HUD:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

6. Was there any necessary information missing from the Full HUD:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

7. Was there any unnecessary information provided by the full HUD:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

8. Were there any safety issues associated with the Full HUD:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

9. What strategy did you incorporate for using the Full HUD in the Precision Approach Task?

10. Please provide any additional comments or design alternatives that you may have regarding the Full HUD.

The Basic HUD with the Runway Symbol Design

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Basic HUD with the Runway Symbol design** in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E). The first table applies to the approach segment *before* the sensor image was available. The second table applies to the approach segment *after* the sensor image was available.

Acceptability Scale

- **A. Very acceptable:** All information readily available and easily interpreted.
- **B. Moderately acceptable:** All information available and interpretable; minor issues having no impact on pilot performance.
- **C. Borderline:** Incomplete information and/or troublesome interpretation; changes would be desirable.
- **D. Moderately unacceptable:** Lack of information and/or difficult interpretations impair pilot performance; corrections required.
- **E. Very unacceptable:** Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

1. *Before* the sensor image/visual scene was available: OTW Condition	With Sensor	Corner Reflectors	No Sensor
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			

Comments:

2. After the sensor image/visual scene was available:	OTW Condition: VMC	With Sensor	Corner Reflectors
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			
g) Determine desired touchdown point			

Comments:

3. Use the above Acceptability Scale to rate the overall acceptability of the Basic HUD with the Runway Symbol design. _____

4. Use the Modified Cooper Harper Scale (last page of this package) to rate the workload associated with the Basic HUD with the Runway Symbol design in each of the following conditions:

   a. VMC _____

   b. With a sensor image _____

   c. With the corner reflectors _____

   d. Without a sensor image _____

5. Did you experience any clutter problems with the Basic HUD with the Runway Symbol design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

6. Was there any necessary information missing from the Basic HUD with the Runway Symbol design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

7. Was there any unnecessary information provided by the Basic HUD with the Runway Symbol design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

8. Were there any safety issues associated with the Basic HUD with the Runway Symbol design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

9. What strategy did you incorporate for using the Basic HUD with the Runway Symbol design in the Precision Approach Task?

10. Please provide any additional comments or design alternatives that you may have regarding the Basic HUD with the Runway Symbol design.

The Basic HUD with the Raw Deviation Data Design

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Basic HUD with the Raw Deviation Data** design in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E). The first table applies to the approach segment *before* the sensor image was available. The second table applies to the approach segment *after* the sensor image was available.

Acceptability Scale

- **A. Very acceptable:** All information readily available and easily interpreted.
- **B. Moderately acceptable:** All information available and interpretable; minor issues having no impact on pilot performance.
- **C. Borderline:** Incomplete information and/or troublesome interpretation; changes would be desirable.
- **D. Moderately unacceptable:** Lack of information and/or difficult interpretations impair pilot performance; corrections required.
- **E. Very unacceptable:** Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

1. *Before* the sensor image/visual scene was available: (OTW Condition)	With Sensor	Corner Reflectors	No Sensor
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			

Comments:

2. After the sensor image/visual scene was available:	OTW Condition VMC	With Sensor	Corner Reflectors
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			
g) Determine desired touchdown point			

Comments:

3. Use the above Acceptability Scale to rate the overall acceptability of the Basic HUD with the Raw Deviation Data design. _____

4. Use the Modified Cooper Harper Scale (last page of this package) to rate the workload associated with the Basic HUD with the Raw Deviation Data design in each of the following conditions:

   a. VMC _____

   b. With a sensor image _____

   c. With the corner reflectors _____

   d. Without a sensor image _____

5. Did you experience any clutter problems with the Basic HUD with the Raw Deviation Data design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

6. Was there any necessary information missing from the Basic HUD with the Raw Deviation Data design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

7. Was there any unnecessary information provided by the Basic HUD with the Raw Deviation Data design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

8. Were there any safety issues associated with the Basic HUD with the Raw Deviation Data design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

9. What strategy did you incorporate for using the Basic HUD with the Raw Deviation Data design in the Precision Approach Task?

10. Please provide any additional comments or design alternatives that you may have regarding the Basic HUD with the Raw Deviation Data design.

The Basic HUD with Both the Runway Symbol and Raw Deviation Design

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Basic HUD with both the Runway Symbol and Raw Deviation Data** design in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E). The first table applies to the approach segment *before* the sensor image was available. The second table applies to the approach segment *after* the sensor image was available.

Acceptability Scale

A. **Very acceptable:** All information readily available and easily interpreted.
B. **Moderately acceptable:** All information available and interpretable; minor issues having no impact on pilot performance.
C. **Borderline:** Incomplete information and/or troublesome interpretation; changes would be desirable.
D. **Moderately unacceptable:** Lack of information and/or difficult interpretations impair pilot performance; corrections required.
E. **Very unacceptable:** Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

1. *Before* the sensor image/visual scene was available:	OTW Condition: With Sensor	Corner Reflectors	No Sensor
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			

Comments:

2. *After the sensor image/visual scene was available:*	OTW Condition: VMC	With Sensor	Corner Reflectors
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			
g) Determine desired touchdown point			

Comments:

3. Use the above Acceptability Scale to rate the overall acceptability of the Basic HUD with both the Runway Symbol and Raw Deviation Data design. _____

4. Use the Modified Cooper Harper Scale (last page of this package) to rate the workload associated with the Basic HUD with both the Runway Symbol and Raw Deviation Data design in each of the following conditions:

   a. VMC _____

   b. With a sensor image _____

   c. With the corner reflectors _____

   d. Without a sensor image _____

5. Did you experience any clutter problems with the Basic HUD with both the Runway Symbol and Raw Deviation Data design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

6. Was there any necessary information missing from the Basic HUD with both the Runway Symbol and Raw Deviation Data design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

7. Was there any unnecessary information provided by the Basic HUD with both the Runway Symbol and Raw Deviation Data design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

8. Were there any safety issues associated with the Basic HUD with both the Runway Symbol and Raw Deviation Data design:
   a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

   b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

9. What strategy did you incorporate for using the Basic HUD with both the Runway Symbol and Raw Deviation Data design in the Precision Approach Task?

10. Please provide any additional comments or design alternatives that you may have regarding the Basic HUD with both the Runway Symbol and Raw Deviation Data design.

Some General Questions

The Experimental HUD Configurations

1. Overall, which HUD configuration did you *most* prefer? Why?

2. Overall, which HUD configuration did you *least* prefer? Why?

3. Did you experience any problems associated with the design and mechanization of any of the individual HUD symbols? If so, please explain.

The TRAC Simulator

Instructions: Use the scale below to rate the acceptability of the following simulator features.

- **A. Very acceptable:** A good simulation as is.
- **B. Moderately acceptable:** Minor simulation deficiencies exist that do not impact pilot performance.
- **C. Borderline:** Simulation deficiencies exist that could impact pilot performance; improvements would be desirable.
- **D. Moderately unacceptable:** Simulation deficiencies degrade pilot performance; improvements required.
- **E. Very unacceptable:** Simulation is too deficient to provide the intended function.

1. Flight characteristics _____
2. Throttle characteristics _____
3. Out-the-Window display _____
4. Sensor image representation _____
5. HUD representation _____
6. Cockpit geometry _____

7. Were you able to adapt to the simulator aeromodel in a reasonable period? Yes _____ No _____. If No, please comment.

8. Were the random winds adequate at inducing a nominal amount of pilot control in order to remain on course and glideslope? Yes _____ No _____.

9. Was the Out-the-Window scene commensurate with your experience with approaches in low visibility conditions? Yes _____ No _____. If No, please comment.

The ALG Concept

1. Do you think there is a future for ALG in the major commercial passenger and freight industry? Yes _____ No _____. Comments:

2. Using an ALG display similar to the one in this evaluation, would you be comfortable flying low visibility approaches? Yes _____ No _____. Comments:

ALG PROGRAM CRITIQUE

1. The billeting and other accommodations during your stay were: poor fair good

Comments: ____

____

____

____

2. Generally speaking, the TRAC test facility (simulation bay, pilots' briefing room, etc.) was: poor fair good

Comments: ____

____

____

____

3. Please rate the experimenters':

	knowledge	poor	fair	good
	professionalism	poor	fair	good
	preparedness	poor	fair	good

Comments: ____

____

____

____

4. Please evaluate the following components of the ALG program:

a)	ground training as a whole	poor	fair	good
	introduction and administration (ground training session one)	poor	fair	good
	cockpit layout (ground training session two)	poor	fair	good
	HUD format and symbology (ground training session three)	poor	fair	good

Comments: ____

____

____

____

b)	flight training as a whole	poor	fair	good
	simulator/display familiarization (flight training session one)	poor	fair	good
	proficiency verification (flight training session two)	poor	fair	good

Comments ____

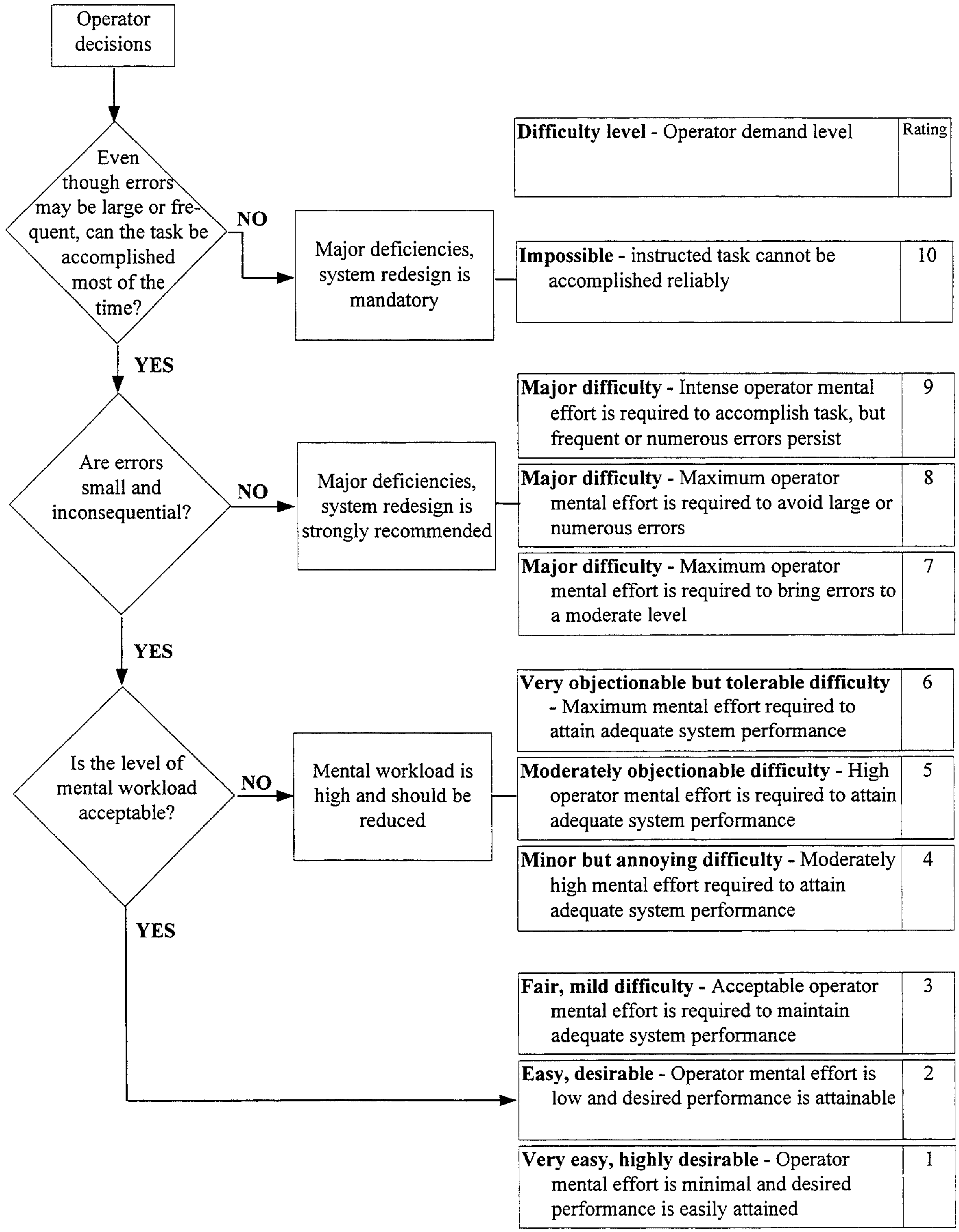
c.	data collection process as a whole	poor	fair	good
	data collection sessions	poor	fair	good
	post-data collection surveys and forms	poor	fair	good

Comments: ____

5. What did you like the most about participating in the ALG study? ________________

6. What did you like the least about participating in the ALG study? ________________

Modified Cooper-Harper Scale



APPENDIX B - ANALYSIS OF VARIANCE RESULTS

STATISTICS SUMMARY

1. Introduction

The results of the analysis procedures performed on the Precision Approach Task and workload data are provided in this Appendix. For each variable, the first table provides the results of ad-hoc Analysis of Variance (ANOVA) procedures and includes F statistics, degrees of freedom, and significance levels for each main and interaction effect. Results of post-hoc ANOVAs and Duncan tests are also provided. Finally, the means for all test conditions are provided.

2. Precision Approach Task Performance Data

The analyses treated in this section pertain to the data collected in the Precision Approach Task. The analyses will be presented separately for each dependent variable.

2.1 Root Mean Square Glideslope Deviation

A 4×4×2 ANOVA (4 head-up displays (HUDs), 4 Sensor/Visibility Conditions, and 2 Approach Segments) was performed on the Root Mean Square (RMS) glideslope deviation data. The results are provided in Table B-1.

Table B-1. ANOVA Results for RMS Glideslope Deviation

Tested Effect	ANOVA Results
HUD	$F(3,33) = 52.87$; $p = .000$
Approach Segment	$F(1,11) = 110.41$; $p = .000$
Sensor/Visibility	$F(3,33) = 0.22$; $p = .347$
HUD × Approach Segment	$F(3,33) = 19.99$; $p = .000$
HUD × Sensor/Visibility	$F(9,99) = 2.99$; $p = .003$
Approach Segment × Sensor/Visibility	$F(3,33) = 0.23$; $p = .877$
HUD × Approach Segment × Sensor/Visibility	$F(9,99) = 2.51$; $p = .012$

The significant three-way interaction between HUD Symbology Set, Approach Segment, and Sensor/Visibility Condition was treated by testing the HUD Symbology Set by

Sensor/Visibility Condition interaction separately for each Approach Segment (Long and Short Final). This interaction was significant for the Short Final Approach Segment, $F(9,99) = 3.10$; $p = .003$, but not for the Long Final Approach Segment, $F(9,99) = 0.95$; $p = .484$. Post-hoc one-way ANOVAs were applied to the Short Final Approach Segment data to test for performance differences across HUD Symbology Sets for each Sensor/Visibility Condition. The results of the ANOVAs are shown in Table B-2. Additional post-hoc one-way ANOVAs were applied to the Short Final Approach Segment data to test for performance differences across the Sensor/Visibility Conditions for each HUD Symbology Set. The results of these tests are shown in Table B-3.

Table B-2. Post-Hoc RMS Glideslope Analyses

Tested Effect	ANOVA Results
HUD × (VMC; Short Final)	$F(3,33) = 15.64$; $p = .000$
HUD × (FLIR; Short Final)	$F(3,33) = 27.15$; $p = .000$
HUD × (Corner Reflectors; Short Final)	$F(3,33) = 14.03$; $p = .000$
HUD × (No Sensor; Short Final)	$F(3,33) = 41.50$; $p = .000$

Table B-3. Post-Hoc RMS Glideslope Analyses

Tested Effect	ANOVA Results
Sensor/Visibility × (Basic/RWY, Short Final)	$F(3,33) = 3.78$; $p = .020$
Sensor/Visibility × (Basic/RAW, Short Final)	$F(3,33) = 0.80$; $p = .505$
Sensor/Visibility × (Basic/BOTH, Short Final)	$F(3,33) = 0.15$; $p = .930$
Sensor/Visibility × (Full HUD, Short Final)	$F(3,33) = 0.67$; $p = .578$

The mean glideslope deviations are shown for each Approach Segment in Tables B-4 and B-5. Duncan Multiple Range tests were conducted on the means associated with the significant one-way tests. The results of the Duncan tests indicated that during the Short Final Approach Segment with the Basic/RWY HUD Symbology Set, RMS glideslope performance with the FLIR and No Sensor Sensor/Visibility Conditions differed significantly from the VMC Condition. In addition, the values of RMS glideslope during the Short Final Approach Segment with the Basic/RWY HUD and the No Sensor Sensor/Visibility

Condition were significantly different from the Corner Reflector Condition. The Duncan tests also indicated that during the Short Final Approach Segment in all of the Sensor/Visibility Conditions, the RMS glideslope deviations with the Basic/RWY HUD were significantly larger than those for the other three HUD Symbology Sets.

Table B-4. Means Used in Post-Hoc RMS Glideslope Analyses

Long Final					
	VMC	FLIR	Corner Reflectors	No Sensor	Overall
Basic/RWY	.560	.617	.608	.702	.622
Basic/RAW	.094	.124	.075	.103	.099
Basic/BOTH	.101	.098	.104	.108	.102
Full	.137	.117	.152	.137	.136
Overall	.224	.239	.235	.264	.241

Table B-5. Means Used in Post-Hoc RMS Glideslope Analyses

Short Final					
	VMC	FLIR	Corner Reflectors	No Sensor	Overall
Basic/RWY	1.423	1.821	1.561	1.956	1.69
Basic/RAW	0.620	0.601	0.678	0.478	.594
Basic/BOTH	0.654	0.636	0.635	0.573	.624
Full	0.853	0.780	0.875	0.724	.808
Overall	.890	.960	.938	.935	.931

2.2 RMS Localizer Deviation

A 4×4×2 ANOVA (4 HUDs, 4 Sensor/Visibility Conditions, and 2 Approach Segments) was performed on the RMS localizer deviation data. The results are provided in Table B-6.

Table B-6. ANOVA Results for RMS Localizer Deviation

Tested Effect	ANOVA Result
HUD	$F(3,33) = 5.84$; $p = .003$
Approach Segment	$F(1,11) = 8.21$; $p = .015$
Sensor/Visibility	$F(3,33) = 1.74$; $p = .177$
HUD × Approach Segment	$F(3,33) = 2.44$; $p = .081$
HUD × Sensor/Visibility	$F(9,99) = 0.92$; $p = .513$
Approach Segment × Sensor/Visibility	$F(3,33) = 6.86$; $p = .001$
HUD × Approach Segment × Sensor/Visibility	$F(9,99) = 1.53$; $p = .146$

A post-hoc ANOVA was performed on the RMS localizer deviation data for the significant interaction between the Approach Segment and Sensor/Visibility conditions. The results showed a significant main effect of the Sensor/Visibility Condition for the Short Final Approach Segment, $F(3,33) = 12.08$; $p = .000$, but not for the Long Final Approach Segment, $F(3,33) = 2.25$; $p = .101$. A Duncan test indicated that RMS localizer performance in the VMC Sensor/Visibility Condition differed significantly from that in the No Sensor Condition during the Short Final Approach Segment. The means for this analysis are shown in Table B-7.

Table B-7. Means Used in the Post-Hoc Analysis of RMS Localizer Deviation

	Long Final	Short Final
VMC	0.122	0.077
FLIR	0.104	0.100
Corner Reflectors	0.108	0.099
No Sensor	0.120	0.128

A Duncan test was also applied to the main effect of the HUD Symbology Set. The results of the Duncan test showed that RMS localizer deviations with the Full HUD and Basic/RWY HUD Symbology Sets were significantly larger than those for the Basic/RAW and the Basic/BOTH HUD Symbology Sets. Means for the different HUD Symbology Sets as a function of Sensor/Visibility Condition are shown in Tables B-8 and B-9 for the Long and Short Final Approach Segments respectively.

Table B-8. Means Used in the Post-Hoc Analysis of RMS Localizer Deviation

Long Final					
	VMC	FLIR	Corner Reflectors	No Sensor	Overall
Basic/RWY	.117	.146	.145	.153	.140
Basic/RAW	.087	.082	.092	.105	.092
Basic/BOTH	.124	.089	.096	.106	.103
Full	.161	.097	.099	.116	.118
Overall	.122	.104	.108	.120	.113

Table B-9. Means Used in the Post-Hoc Analysis of RMS Localizer Deviation

Short Final					
	VMC	FLIR	Corner Reflectors	No Sensor	Overall
Basic/RWY	.073	.111	.106	.121	.103
Basic/RAW	.071	.091	.080	.116	.089
Basic/BOTH	.076	.085	.078	.119	.090
Full	.089	.115	.132	.150	.121
Overall	.077	.100	.099	.126	.101

2.3 Vertical Velocity

A 4×4×2 ANOVA (4 HUDs, 4 Sensor/Visibility Conditions, and 2 Approach Segments) was performed on the RMS vertical velocity data. The results are provided in Table B-10.

Table B-10. ANOVA Results for RMS Vertical Velocity

Tested Effect	ANOVA Result
HUD	$F(3,33) = 16.60$; $p = .000$
Approach Segment	$F(1,11) = 69.49$; $p = .000$
Sensor/Visibility	$F(3,33) = 0.85$; $p = .478$
HUD × Approach Segment	$F(3,33) = 23.31$; $p = .000$
HUD × Sensor/Visibility	$F(9,99) = 3.13$; $p = .002$
Approach Segment × Sensor/Visibility	$F(3,33) = 3.01$; $p = .044$
HUD × Approach Segment × Sensor/Visibility	$F(9,99) = 0.51$; $p = .863$

The significant interaction between the HUD Symbology Set and the Approach Segment for RMS vertical velocity was investigated with a post-hoc one-way ANOVA testing for differences across the HUD Symbology Set for the Long and Short Final Approach

Segments. The results showed a significant main effect for the HUD Symbology Set during the Short Final Approach Segment, $F(3,33) = 23.68$; $p = .000$, but not during the Long Final Approach Segment, $F(3,33) = 1.00$; $p = .406$. A Duncan test showed that the values of vertical velocity for the Basic/RWY HUD Symbology Set were significantly different from each of the other HUD Symbology Sets. In addition, this Duncan test revealed a significant difference in the values of vertical velocity between the Basic/RAW HUD Symbology Set and the Full HUD.

The significant interaction of the HUD Symbology Set and the Sensor/Visibility Condition on RMS vertical velocity was investigated with a series of post-hoc one-way ANOVAs. The results are provided in Table B-11. The effect of the HUD Symbology Set as a function of the Sensor/Visibility Condition was significant for the FLIR, Corner Reflectors, and No Sensor conditions. The differences among HUD Symbology Sets were investigated with a post-hoc Duncan test, which indicated that vertical velocity deviations were smallest with the Basic/RWY Symbology Set for all Sensor/Visibility Conditions. The means used in these evaluation are provided in Tables B-12, B-13, and B-14.

Table B-11. Post-Hoc RMS Vertical Velocity Analysis - HUD Symbology Set by Sensor/Visibility Condition Interaction

Tested Effect	**ANOVA Result**
HUD (VMC)	$F(3,33) = 1.94$; $p = .143$
HUD (FLIR)	$F(3,33) = 7.60$; $p = .001$
HUD (Corner Reflectors)	$F(3,33) = 7.63$; $p = .001$
HUD (No Sensor)	$F(3,33) = 18.41$; $p = .000$

Table B-12. Means Used in the Post-Hoc Analysis of RMS Vertical Velocity

Long Final					
	VMC	FLIR	Corner Reflectors	No Sensor	Overall
Basic/RWY	1150.72	1133.67	1137.76	1116.31	1134.62
Basic/RAW	1117.65	1125.66	1131.41	1129.22	1125.98
Basic/BOTH	1125.06	1124.32	1139.12	1115.51	1126.01
Full	1141.03	1120.40	1131.07	1132.04	1131.13
Overall	1133.71	1126.01	1134.88	1123.18	1129.44

Table B-13. Means Used in the Post-Hoc Analysis of RMS Vertical Velocity

	Short Final				
	VMC	FLIR	Corner Reflectors	No Sensor	Overall
Basic/RWY	1033.89	993.88	1004.63	1005.21	1009.40
Basic/RAW	1089.15	1105.22	1100.74	1140.06	1108.79
Basic/BOTH	1097.04	1092.54	1096.31	1094.66	1095.12
Full	1078.43	1077.88	1075.56	1092.24	1080.96
Overall	1074.39	1067.37	1069.24	1082.95	1073.47

Table B-14. Means Used in the Post-Hoc Analysis of RMS Vertical Velocity

	VMC	FLIR	Corner Reflectors	No Sensor
Basic/RWY	1092.30	1063.78	1071.19	1060.76
Basic/RAW	1103.40	1115.44	1116.07	1134.64
Basic/BOTH	1111.05	1108.43	1117.71	1105.09
Full	1109.73	1099.14	1103.32	1112.06

The significant interaction between the Approach Segment and the Sensor/Visibility Condition for RMS vertical velocity was investigated with a post-hoc ANOVA. No significant effects were found for the Long Final, $F(3,33) = 1.64$; $p = .199$, or Short Final Approach Segments, $F(3,33) = 2.47$; $p = .079$.

2.4 Indicated Airspeed

A 4×4×2 ANOVA (4 HUDs, 4 Sensor/Visibility Conditions, and 2 Approach Segments) was performed on the RMS indicated airspeed (IAS) data. The results are provided in Table B-15.

Table B-15. ANOVA Results for RMS Indicated Airspeed

Tested Effect	**ANOVA Result**
HUD	$F(3,33) = 2.45$; $p = .081$
Approach Segment	$F(1,11) = 0.10$; $p = .753$
Sensor/Visibility	$F(3,33) = 3.58$; $p = .024$
HUD × Approach Segment	$F(3,33) = 4.18$; $p = .013$
HUD × Sensor/Visibility	$F(9,99) = 2.46$; $p = .014$
Approach Segment × Sensor/Visibility	$F(3,33) = 0.34$; $p = .796$
HUD × Approach Segment × Sensor/Visibility	$F(9,99) = 0.50$; $p = .872$

The significant interactions of the HUD Symbology Set and the Approach Segment on RMS IAS, as well as HUD Symbology Set and Sensor/Visibility Condition on RMS IAS, were investigated with post-hoc ANOVAs. The results of the analysis involving the interaction of the HUD Symbology Set and the Approach Segment revealed a significant main effect of HUD Symbology Set for both the Long Final, $F(3,33) = 3.14$; $p = .038$, and Short Final, $F(3,33) = 2.98$; $p = .045$ Approach Segments. For the Long Final Approach Segment, Duncan tests showed that RMS IAS deviations were the smallest for the Basic/RWY HUD Symbology Set. For the Short Final Approach Segment, RMS IAS deviations were smaller for the Basic/RWY and Basic/RAW Symbology Sets than for the Basic/BOTH and Full HUD Symbology Sets.

The post-hoc analysis of the HUD Symbology Set by the Sensor/Visibility Condition interaction are shown in Table B-16. As the table shows, a significant main effect for HUD Symbology Set was found for both the VMC and No Sensor Conditions. For the VMC Condition, a Duncan test showed that RMS IAS deviations were larger for the Full HUD Symbology Set than for the Basic/RAW and Basic/BOTH Symbology Sets. For the No Sensor Condition, a Duncan test showed that RMS IAS deviations for both the Basic/RAW and Full HUD Symbology Sets were significantly larger than for the Basic/Both Symbology Set.

Table B-16. Post-Hoc RMS Indicated Airspeed Analysis - HUD Symbology Set by Sensor/Visibility Condition Interaction

Tested Effect	ANOVA Result
HUD (VMC)	$F(3,33) = 3.16$; $p = .038$
HUD (FLIR)	$F(3,33) = 0.75$; $p = .532$
HUD (Corner Reflectors)	$F(3,33) = 2.26$; $p = .100$
HUD (No Sensor)	$F(3,33) = 3.64$; $p = .023$

The means used in the above analyses are provided in Table B-17, B-18, and B-19.

Table B-17. Means Used in the Post-Hoc Analysis of RMS Indicated Airspeed

Long Final					
	VMC	FLIR	Corner Reflectors	No Sensor	Overall
Basic/RWY	3.68	3.01	3.25	3.32	3.315
Basic/RAW	3.37	3.80	4.23	4.79	4.049
Basic/BOTH	3.93	4.13	4.42	3.75	4.057
Full	4.13	3.48	3.42	4.75	3.941
Overall	3.775	3.603	3.832	4.149	3.839

Table B-18. Means Used in the Post-Hoc Analysis of RMS Indicated Airspeed

Short Final					
	VMC	FLIR	Corner Reflectors	No Sensor	Overall
Basic/RWY	3.87	3.62	3.77	4.55	3.951
Basic/RAW	3.34	3.77	4.77	4.80	4.173
Basic/BOTH	3.19	3.59	3.51	3.37	3.418
Full	4.39	4.06	4.01	4.76	4.302
Overall	3.702	3.761	4.016	4.367	3.961

Table B-19. Means Used in the Post-Hoc Analysis of RMS Indicated Airspeed

	VMC	FLIR	Corner Reflectors	No Sensor
Basic/RWY	3.78	3.31	3.51	3.93
Basic/RAW	3.35	3.79	4.50	4.80
Basic/BOTH	3.56	3.86	3.96	3.56
Full	4.26	3.77	3.71	4.61

2.5 Touchdown Deviation

A 4×4 ANOVA (4 HUDs by 4 Sensor/Visibility Conditions) was done on the touchdown deviation from the runway point of intercept (RPI) data. See Table B-20 for the results.

Table B-20. ANOVA Results for Touchdown Deviation from RPI Data

Tested Effect	**ANOVA Result**
HUD	$F(3,33) = 3.48;\ p = .027$
Sensor/Visibility	$F(3,30) = 0.13;\ p = .941$
HUD × Sensor/Visibility	$F(9,89) = 2.01;\ p = .046$

The significant two-way interaction between the HUD Symbology Set and the Sensor/Visibility Condition was treated by using post-hoc one-way ANOVAs to test for RPI touchdown deviation differences across HUD Symbology Sets for each Sensor/Visibility Condition. The results of these post-hoc ANOVAs are shown in Table B-21. Post-hoc one-way ANOVAs were also used to test for RPI touchdown deviation differences across Sensor/Visibility Conditions for each HUD Symbology Set. The results of these post-hoc ANOVAs are shown in Table B-22. Significant differences across HUD Symbology Sets were only detected for the VMC Sensor/Visibility Condition. A Duncan test indicated that RPI touchdown deviations were larger with the Full HUD Symbology Set than for any of the other HUD Symbology Sets. Since no significant differences were found across the Sensor/Visibility Conditions for any of the HUD Symbology Sets, no further analysis was completed.

Table B-21. Post-Hoc RPI Touchdown Deviation Analyses

Tested Effect	ANOVA Results
HUD × (VMC)	$F(3,33) = 3.81;\ p = .019$
HUD × (FLIR)	$F(3,33) = 0.93;\ p = .439$
HUD × (Corner Reflectors)	$F(3,33) = 2.23;\ p = .103$
HUD × (No Sensor)	$F(3,33) = 0.18;\ p = .910$

Table B-22. Post-Hoc RPI Touchdown Deviation Analyses

Tested Effect	ANOVA Results
Sensor/Visibility × (Basic/RWY)	$F(3,33) = 1.27;\ p = .301$
Sensor/Visibility × (Basic/RAW)	$F(3,33) = 0.69;\ p = .566$
Sensor/Visibility × (Basic/BOTH)	$F(3,33) = 1.24;\ p = .311$
Sensor/Visibility × (Full HUD)	$F(3,33) = 2.74;\ p = .060$

The means used in this analysis are provided in Table B-23.

Table B-23. Means Used in the Analysis of RPI Touchdown Deviation

	VMC	FLIR	Corner Reflectors	No Sensor	Overall
Basic/RWY	278.29	382.60	350.23	407.39	349.73
Basic/RAW	290.04	253.30	230.52	286.94	264.88
Basic/BOTH	296.57	251.26	300.77	254.61	276.07
Full	409.62	383.43	389.22	295.27	371.44
Overall	316.91	316.89	314.87	305.45	

2.6 Centerline Deviation

A 4×4 ANOVA (4 HUDs and 4 Sensor/Visibility Conditions) was performed on the centerline deviation data. The results are provided in Table B-24. A significant main effect was found for Sensor/Visibility Conditions. A post-hoc Duncan test showed that centerline deviations for the Corner Reflector and No Sensor Conditions were significantly larger than for those in the VMC and FLIR Conditions. The means used in this evaluation are provided in Table B-25.

Table B-24. ANOVA Results for Centerline Deviation Data

Tested Effect	**ANOVA Result**
HUD	$F(3,33) = 0.75$; $p = .532$
Sensor/Visibility	$F(3,33) = 7.05$; $p = .001$
HUD × Sensor/Visibility	$F(9,98) = 0.68$; $p = .723$

Table B-25. Means Used in the Analysis of Centerline Deviation

	VMC	FLIR	Corner Reflectors	No Sensor	Overall
Basic/RWY	12.37	13.07	26.63	18.62	17.49
Basic/RAW	12.31	13.14	15.33	17.51	14.46
Basic/BOTH	11.38	13.45	21.46	17.17	15.90
Full	17.32	12.24	20.60	18.14	17.01
Overall	13.29	12.98	20.96	17.80	

3. Workload Data

A 4×2 ANOVA (4 HUDs and 2 Approach Segments) was performed on the workload ratings gathered with the Subjective WORkload Dominance (SWORD) technique. The results are provided in Table B-26.

Table B-26. ANOVA Results for Workload Ratings

Tested Effect	**ANOVA Result**
HUD	$F(3,33) = 4.46;\ p = .010$
Approach Segment	$F(1,11) = 3.51;\ p = .088$
HUD × Approach Segment	$F(3,33) = 2.16;\ p = .111$

The significant main effect of HUD on workload was further investigated with a post-hoc Duncan test, which showed that workload ratings for the Full HUD were significantly larger than those for the Basic/BOTH Symbology Set but did not differ from those for the Basic/RWY and Basic/RAW Sets.

The means used in this analysis are provided in Table B-27.

Table B-27. Means Used in the Workload Analysis

	Basic/RWY	Basic/RAW	Basic/BOTH	Full
Mean	0.1458	0.0933	0.0840	0.1768

APPENDIX C - SUMMARY OF QUESTIONNAIRE RESPONSES

Introduction

The questionnaire used in the Head-Up Display (HUD) Symbology Evaluation for the Autonomous Landing Guidance (ALG) System is provided in Appendix A. The responses of the 12 pilots who participated in this study are summarized in this Appendix. Where appropriate, the responses are summarized in tables. Comments provided by the pilots have also been recorded.

Question 1. Full HUD Symbology Set

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Full HUD Symbology Set** in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E).

Acceptability Scale

A. Very acceptable: All information readily available and easily interpreted.

B. Moderately acceptable: All information available and interpretable; minor issues having no impact on pilot performance.

C. Borderline: Incomplete information and/or troublesome interpretation ; changes would be desirable.

D. Moderately unacceptable: Lack of information and/or difficult interpretations impair pilot performance; corrections required.

E. Very unacceptable: Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

1. *Before* the sensor image/visual scene was available: OTW Condition	With Sensor	Corner Reflectors	No Sensor
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			

Table C-1 represents the frequency with which each of the above Acceptability Ratings were used to respond to the above matrix in regards to the Full HUD Symbology Set.

Table C-1. Frequency of Acceptability Rating Responses to Question 1 Regarding the Full HUD Symbology Set

	Rating	1a. With Sensor	1b. With Sensor	1c. With Sensor	1d. With Sensor	1e. With Sensor	1f. With Sensor	1a. Corner Reflectors	1b. Corner Reflectors	1c. Corner Reflectors	1d. Corner Reflectors	1e. Corner Reflectors	1f. Corner Reflectors	1a. No Sensor	1b. No Sensor	1c. No Sensor	1d. No Sensor	1e. No Sensor	1f. No Sensor
Full HUD	**A**	4	3	3	4	3	5	4	2	3	3	2	5	4	2	3	3	2	5
	B	4	4	4	5	7	5	4	5	5	6	8	6	1	4	3	5	6	3
	C	4	5	5	3	1	2	4	5	4	3	1	1	5	4	4	3	3	3
	D	0	0	0	0	1	0	0	0	0	0	1	0	2	2	2	1	1	1
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Comments:

Pilot 1: Strongly suggest fitting a contrast feature to clearly define the differences between the projected HUD information which is green, and the bright white day time cloud background. With the Full HUD data display selected, it was sometimes impossible to make out the different HUD depiction's, especially the vertical course references.

Pilot 2: Very cluttered display that gets more confusing with increasing errors. "No Sensor" has very poor contrast and hard to see overall.

Pilot 5: Remove some of the clutter. Suggestions: "VanHalen" (aircraft reference) symbol, speed-worm. At times I had difficulty discerning my glideslope and course information (critical information) from other not so critical information.

Pilot 7: The Full HUD contained too much information and was overwhelming. The following symbols need to be removed: AIRCRAFT nose pointer; vertical dot scale (see drawing); tail yaw indicator; flare indicator; runway rise indicator; runway marker (only until short final - e.g., 2 nm); acceleration cue (not needed when beginning landing transition). Additionally, I would like to see the flight path marker and pitch scale look something like this: (see drawing). The acceleration cue and airspeed bar are nice to have indications, but the scale is too small (i.e., small deviations result in large marked displacement).

Pilot 11: Display in General/Symbols Used: Miniature AIRCRAFT...pitch symbol is too large, needs to be smaller and a different shape, the U.S. Mil symbol used on ADIs would be fine; Flight Path Marker...unfamiliar shape. The "legs" don't do anything except identify the symbol as the FPM. Change symbol to (see drawing), wings and tail can be used to overlay other

symbols; Digital Readouts -- make more work than analog pointers; Digital VVI..."sucks."

Pilot 12: Before sensor image/visual acquisition, all modes were identical in the "full HUD" design. The Aircraft symbol/lubber line was distracting and should be eliminated.

Question 1. Basic/RWY HUD Symbology Set

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Basic/RWY HUD Symbology Set** in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E).

Acceptability Scale

A. Very acceptable: All information readily available and easily interpreted.

B. Moderately acceptable: All information available and interpretable; minor issues having no impact on pilot performance.

C. Borderline: Incomplete information and/or troublesome interpretation ; changes would be desirable.

D. Moderately unacceptable: Lack of information and/or difficult interpretations impair pilot performance; corrections required.

E. Very unacceptable: Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

1. *Before* the sensor image/visual scene was available: OTW Condition	With Sensor	Corner Reflectors	No Sensor
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			

Table C-2 represents the frequency with which each of the above Acceptability Ratings were used to respond to the matrix in regards to the Basic/RWY HUD Symbology Set.

Table C-2. Frequency of Acceptability Rating Responses to Question 1 Regarding the Basic/RWY HUD Symbology Set

	Rating	1a. With Sensor	1b. With Sensor	1c. With Sensor	1d. With Sensor	1e. With Sensor	1f. With Sensor	1a. Corner Reflectors	1b. Corner Reflectors	1c. Corner Reflectors	1d. Corner Reflectors	1e. Corner Reflectors	1f. Corner Reflectors	1a. No Sensor	1b. No Sensor	1c. No Sensor	1d. No Sensor	1e. No Sensor	1f. No Sensor
Basic/RWY	**A**	3	1	1	1	2	1	3	1	2	1	2	1	2	1	0	1	1	0
	B	3	5	4	9	6	6	3	5	3	8	5	6	1	4	3	6	6	6
	C	2	4	2	1	3	2	3	3	3	2	3	2	5	3	3	3	2	2
	D	4	2	4	1	1	3	3	3	4	1	2	3	4	3	6	2	3	4
	E	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0

Comments:

Pilot 1: Much easier to work with than the Full HUD. The flight path indicator makes it a lot easier to anticipate the actual aircraft flight path, and to put in corrections ahead of time instead of reacting to changed aircraft conditions.

Pilot 2: See my general comments.

Pilot 3: Basic/RWY is near impossible to attain centerline more than 1 mile out.

Pilot 5: Runway symbol does provide crude course and glideslope information, but is not sufficient for flying a precision approach in low visibility conditions. I landed short at least once with this display.

Pilot 6: Cues very subtle! Also, lack of DME hurts the determination of position along the approach path.

Pilot 7: The lack of a definitive glideslope cue really hampered my ability to visualize/determine my position along the glidepath. The Runway perspective (long narrow lines) made me feel that I was consistently high on glideslope. The gull wing FPM allowed for some interpretation as to where the "center" actually was.

Pilot 11: Symbol comments same as before. In general, I learned to use the minimum symbol set...whatever was easiest for me...seldom used other symbology. Background (VFR, sensor reflectors, haze) didn't matter. This display was the hardest to use. Okay if on course and glideslope, but harder to interpret if high or low, left or right. Would make corrections then wait to see what happened.

Question 1. The Basic/RAW HUD Symbology Set

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Basic/RAW HUD Symbology Set** in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E).

Acceptability Scale

A. Very acceptable: All information readily available and easily interpreted.

B. Moderately acceptable: All information available and interpretable; minor issues having no impact on pilot performance.

C. Borderline: Incomplete information and/or troublesome interpretation ; changes would be desirable.

D. Moderately unacceptable: Lack of information and/or difficult interpretations impair pilot performance; corrections required.

E. Very unacceptable: Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

1. *Before* the sensor image/visual scene was available: OTW Condition	With Sensor	Corner Reflectors	No Sensor
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			

Table C-3 represents the frequency with which each of the above Acceptability Ratings were used to respond to the matrix in regards to the Basic/RAW HUD Symbology Set.

Table C-3. Frequency of Acceptability Rating Responses to Question 1 Regarding the Basic/RAW HUD Symbology Set

	Rating	1a. With Sensor	1b. With Sensor	1c. With Sensor	1d. With Sensor	1e. With Sensor	1f. With Sensor	1a. Corner Reflectors	1b. Corner Reflectors	1c. Corner Reflectors	1d. Corner Reflectors	1e. Corner Reflectors	1f. Corner Reflectors	1a. No Sensor	1b. No Sensor	1c. No Sensor	1d. No Sensor	1e. No Sensor	1f. No Sensor
Basic/RAW	**A**	5	5	5	6	5	4	5	6	6	6	5	4	3	4	3	3	3	2
	B	5	4	5	3	5	6	5	3	4	3	5	6	4	5	5	5	7	8
	C	2	2	1	3	1	1	2	2	1	3	1	1	3	1	2	2	0	0
	D	0	1	1	0	1	1	0	1	1	0	1	1	2	2	2	2	2	2
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Comments:

Pilot 2: See general comment page.

Pilot 6: Need DME data or some other way to determine distance from threshold. Contrast problems again in "No Sensor" case.

Pilot 7: Overall easy to fly. A flight director ball would have made it a little easier.

Pilot 11: C ratings = symbol problems. Felt that I performed best with this display, easy to understand, least clutter.

Question 1. The Basic/BOTH HUD Symbology Set

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Basic/BOTH HUD Symbology Set** in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E).

Acceptability Scale

A. Very acceptable: All information readily available and easily interpreted.

B. Moderately acceptable: All information available and interpretable; minor issues having no impact on pilot performance.

C. Borderline: Incomplete information and/or troublesome interpretation ; changes would be desirable.

D. Moderately unacceptable: Lack of information and/or difficult interpretations impair pilot performance; corrections required.

E. Very unacceptable: Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

1. *Before* the sensor image/visual scene was available: (OTW Condition)	With Sensor	Corner Reflectors	No Sensor
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			

Table C-4 represents the frequency with which each of the above Acceptability Ratings were used to respond to the matrix in regards to the Basic/BOTH HUD Symbology Set.

Table C-4. Frequency of Acceptability Rating Responses to Question 1 Regarding the Basic/BOTH HUD Symbology Set

	Rating	1a. With Sensor	1b. With Sensor	1c. With Sensor	1d. With Sensor	1e. With Sensor	1f. With Sensor	1a. Corner Reflectors	1b. Corner Reflectors	1c. Corner Reflectors	1d. Corner Reflectors	1e. Corner Reflectors	1f. Corner Reflectors	1a. No Sensor	1b. No Sensor	1c. No Sensor	1d. No Sensor	1e. No Sensor	1f. No Sensor
Basic/BOTH	**A**	5	4	5	6	5	4	6	5	6	7	6	4	3	3	3	5	4	3
	B	7	7	6	5	6	7	6	6	5	4	5	7	6	7	6	4	6	7
	C	0	1	1	1	1	1	0	1	1	1	1	1	2	1	2	2	1	1
	D	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Comments:

Pilot 2: Having runway symbol helps, but trying to interpret different systems seems to cause confusion if picture isn't "obvious."

Pilot 6: A good set of information except with contrast problems in "No Sensor" cases. No DME...but less of a factor due to runway presence.

Pilot 7: With "No Sensor," contrast is too high...function of simulation display.

Pilot 11: Symbol problems...same. Second easiest to fly. Runway symbol provides most information when close in.

Question 2. Full HUD Symbology Set

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Full HUD Symbology Set** in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E).

Acceptability Scale

A. Very acceptable: All information readily available and easily interpreted.

B. Moderately acceptable: All information available and interpretable; minor issues having no impact on pilot performance.

C. Borderline: Incomplete information and/or troublesome interpretation ; changes would be desirable.

D. Moderately unacceptable: Lack of information and/or difficult interpretations impair pilot performance; corrections required.

E. Very unacceptable: Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

2. *After the sensor image/visual scene was available:* (OTW Condition)	VMC	With Sensor	Corner Reflectors
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			
g) Determine desired touchdown point			

Table C-5 represents the frequency with which each of the above Acceptability Ratings were used to respond to the matrix in regards to the Full HUD Symbology Set.

Table C-5. Frequency of Acceptability Rating Responses to Question 2 Regarding the Full HUD Symbology Set

	Rating	2a. VMC	2b. VMC	2c. VMC	2d. VMC	2e. VMC	2f. VMC	2g. VMC	2a. With Sensor	2b. With Sensor	2c. With Sensor	2d. With Sensor	2e. With Sensor	2f. With Sensor	2g. With Sensor	2a. Corner Reflectors	2b. Corner Reflectors	2c. Corner Reflectors	2d. Corner Reflectors	2e. Corner Reflectors	2f. Corner Reflectors	2g. Corner Reflectors
Full HUD	**A**	7	6	6	5	6	7	7	5	5	5	4	5	7	6	3	5	3	4	5	6	2
	B	2	3	3	5	3	4	3	4	4	4	6	4	4	4	5	3	5	6	3	5	5
	C	3	3	3	2	3	1	2	3	3	3	2	3	1	2	4	4	3	2	3	1	3
	D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	2
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

<u>Comments:</u>

Pilot 1: Overall, once I acquired a good visual with the landing runway (i.e., runway end identifier lights, rabbits, runway markings), I'm out of the instrument mode, and about the only thing I'll reference is the airspeed. The rest is all visual cues.

Pilot 2: Clutter primary problem...even in VMC hard to see runway environment. Becomes worse problem with corner reflectors because cues are more subtle.

Pilot 6: "B" rating given for clutter on Full HUD display. Question 2...at certain points had to look past HUD information to real world. On question 1, the "No Sensor" set was most difficult due to contrast of HUD symbology with gray background.

Pilot 7: Not necessary in VMC. On question 2e: Full HUD tends to obscure OTW view of runway environment in almost all cases. 2g: Same as 2e. Only applied to the desired TD point.

Pilot 10: Full HUD needs to be decluttered. "Flag" doesn't seem appropriate. Add turn rate/slip indicator, i.e., needle and ball. Suggest orange color for "no sensor" IMC for contrast. Full HUD interferes with transition to visual during landing with no sensor.

Pilot 11: Display in General/Symbols Used: Miniature AIRCRAFT...pitch symbol is too large, needs to be smaller and a different shape, the U.S. Mil symbol used on ADIs would be fine; Flight Path Marker...unfamiliar shape. The "legs" don't do anything except identify the symbol as the FPM. Change symbol to (see drawing), wings and tail can be used to overlay other symbols; Digital Readouts...make more work than analog pointers; Digital VVI..."sucks."

Pilot 12: Corner reflectors did not provide enough depth perception for "comfortable" vertical control . . . long landings or firm touchdowns resulted.

Question 2. The Basic/RWY HUD Symbology Set

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Basic/RWY HUD Symbology Set** in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E).

Acceptability Scale

A. Very acceptable: All information readily available and easily interpreted.

B. Moderately acceptable: All information available and interpretable; minor issues having no impact on pilot performance.

C. Borderline: Incomplete information and/or troublesome interpretation ; changes would be desirable.

D. Moderately unacceptable: Lack of information and/or difficult interpretations impair pilot performance; corrections required.

E. Very unacceptable: Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

2. After the sensor image/visual scene was available: OTW Condition	VMC	With Sensor	Corner Reflectors
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			
g) Determine desired touchdown point			

Table C-6 represents the frequency with which each of the above Acceptability Ratings were used to respond to the matrix in regards to the Basic/RWY HUD Symbology Set.

Table C-6. Frequency of Acceptability Rating Responses to Question 2 Regarding the Basic/RWY HUD Symbology Set

	Rating	2a. VMC	2b. VMC	2c. VMC	2d. VMC	2e. VMC	2f. VMC	2g. VMC	2a. With Sensor	2b. With Sensor	2c. With Sensor	2d. With Sensor	2e. With Sensor	2f. With Sensor	2g. With Sensor	2a. Corner Reflectors	2b. Corner Reflectors	2c. Corner Reflectors	2d. Corner Reflectors	2e. Corner Reflectors	2f. Corner Reflectors	2g. Corner Reflectors
Basic/RWY	**A**	6	6	6	7	6	5	7	7	6	3	4	5	3	5	4	5	2	5	5	4	4
	B	3	3	3	3	3	4	3	2	2	5	6	3	5	4	3	2	5	5	3	4	1
	C	2	1	2	1	2	2	1	2	3	3	1	3	3	2	4	4	4	1	3	3	6
	D	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

<u>Comments:</u>

Pilot 1: As long as you've got the correct manually-selected glideslope (the dashed line) indicator depicted, it's easy.

Pilot 2: Fairly good symbology. Could be enhanced with course, DME, winds, etc. Runway symbol accuracy not the greatest but acceptable.

Pilot 6: Symbology was ignored once visual was sighted until flare was used to a mild extent in the corner reflector scenario especially as a flare cue.

Pilot 7: 2a in VMC...runway lines didn't quite interfere with visual, but I could have done without them. (Not necessary). 2a with Sensor was excellent! 2a with corner reflectors tended to overlay and obscure corner reflectors. 2c...vertical deviation tough to judge. 2f...See above.

Pilot 9: The runway "captain's bars" (1,000 foot markers on the runway symbology) are not in sight until short final. This makes it hard to determine where you are on the glidepath when further out on the approach.

Pilot 11: Symbol comments same as before. In general, I learned to use the minimum symbol set...whatever was easiest for me...seldom used other symbology. Background (VFR, sensor reflectors, haze) didn't matter. This display was the hardest to use. Okay if on course and glideslope, but harder to interpret if high or low, left or right. Would make corrections then wait to see what happened.

Question 2. The Basic/RAW HUD Symbology Set

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Basic/RAW HUD Symbology Set** in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E).

Acceptability Scale

A. Very acceptable: All information readily available and easily interpreted.

B. Moderately acceptable: All information available and interpretable; minor issues having no impact on pilot performance.

C. Borderline: Incomplete information and/or troublesome interpretation ; changes would be desirable.

D. Moderately unacceptable: Lack of information and/or difficult interpretations impair pilot performance; corrections required.

E. Very unacceptable: Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

2. *After the sensor image/visual scene was available:* (OTW Condition)	VMC	With Sensor	Corner Reflectors
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			
g) Determine desired touchdown point			

Table C-7 represents the frequency with which each of the above Acceptability Ratings were used to respond to the matrix in regards to the Basic/RAW HUD Symbology Set.

Table C-7. Frequency of Acceptability Rating Responses to Question 2 Regarding the Basic/RAW HUD Symbology Set

	Rating	2a. VMC	2b. VMC	2c. VMC	2d. VMC	2e. VMC	2f. VMC	2g. VMC	2a. With Sensor	2b. With Sensor	2c. With Sensor	2d. With Sensor	2e. With Sensor	2f. With Sensor	2g. With Sensor	2a. Corner Reflectors	2b. Corner Reflectors	2c. Corner Reflectors	2d. Corner Reflectors	2e. Corner Reflectors	2f. Corner Reflectors	2g. Corner Reflectors
Basic/RAW	**A**	8	8	8	7	8	6	9	7	8	5	7	7	7	8	5	6	5	6	6	5	4
	B	3	3	3	3	3	4	2	4	3	6	4	5	4	4	5	5	4	5	5	6	5
	C	1	1	1	2	1	2	1	1	1	1	1	0	1	0	2	1	3	1	1	1	3
	D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Comments:

Pilot 1: Altitude warning indications would be nice; overall the best of the three systems to use.

Pilot 6: Once visual...basically okay.

Pilot 7: Don't need it in VMC. Very helpful with sensor video; it really worked well to determine lateral deviation and touchdown point.

Pilot 11: C ratings = symbol problems. Felt that I performed best with this display, easy to understand, least clutter.

Question 2. The Basic/BOTH HUD Symbology Set

Instructions: The ALG precision approach is segmented into a set of unique tasks in the tables below. Use the Acceptability Scale provided to rate the suitability of the **Basic/BOTH HUD Symbology Set** in the performance of each of these tasks for each of the out-the-window (OTW) conditions identified. Please provide comments and suggested design alternatives for any item rated "borderline or worse" (i.e., C, D, or E).

Acceptability Scale

A. Very acceptable: All information readily available and easily interpreted.

B. Moderately acceptable: All information available and interpretable; minor issues having no impact on pilot performance.

C. Borderline: Incomplete information and/or troublesome interpretation ; changes would be desirable.

D. Moderately unacceptable: Lack of information and/or difficult interpretations impair pilot performance; corrections required.

E. Very unacceptable: Display is unsafe, impractical, and contributes greatly to mission failure; redesign required.

2. After the sensor image/visual scene was available: (OTW Condition)	VMC	With Sensor	Corner Reflectors
a) Safely fly the approach			
b) Monitor and control lateral deviation			
c) Monitor and control vertical deviation			
d) Monitor and control fundamental aircraft performance			
e) Monitor and control ground track			
f) Determine position along the approach path			
g) Determine desired touchdown point			

Table C-8 represents the frequency with which each of the above Acceptability Ratings were used to respond to the matrix in regards to the Basic/BOTH HUD Symbology Set.

Table C-8. Frequency of Acceptability Rating Responses to Question 2 Regarding the Basic/BOTH HUD Symbology Set

	Rating	2a. VMC	2b. VMC	2c. VMC	2d. VMC	2e. VMC	2f. VMC	2g. VMC	2a. With Sensor	2b. With Sensor	2c. With Sensor	2d. With Sensor	2e. With Sensor	2f. With Sensor	2g. With Sensor	2a. Corner Reflectors	2b. Corner Reflectors	2c. Corner Reflectors	2d. Corner Reflectors	2e. Corner Reflectors	2f. Corner Reflectors	2g. Corner Reflectors
Basic/BOTH	**A**	9	8	9	8	9	7	9	7	7	7	7	8	7	7	6	6	7	6	8	4	5
	B	2	2	1	2	2	3	2	5	4	4	4	4	4	5	4	5	3	5	3	6	4
	C	1	2	2	2	1	2	1	0	1	1	1	0	1	0	2	1	2	1	1	2	3
	D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Comments:

Pilot 1: Essentially, the same as the basic HUD with raw deviation data only. The difference between having the runway outline depiction, and just paying attention to the radar altimeter is slight, and not worth the clutter; especially when you're 4 or 5 miles or more out and the dotted course line, the raw data line and the runway all blend together.

Pilot 2: Symbols clutter visual field.

Pilot 7: Not necessary in VMC. All 2s with Sensor outstanding! The only thing I would change from what you have is: 1) take away runway symbol until short (2nm) final; 2) provide flight director ball; and 3) add acceleration cue (until flare) and A/S tape. 2f and 2g with Corner Reflectors...tough to determine 3-D position of touchdown point in close.

Pilot 11: Symbols...same. Second easiest to fly. Runway symbol provides most information when close in.

<u>Question 3.</u> Use the above Acceptability Scale to rate the overall acceptability of each of the HUD Symbology Sets. _____

Table C-9. Frequency of Acceptability Ratings for Question 3

	Full HUD	Basic/RWY	Basic/RAW	Basic/BOTH
A	3	1	4	4
B	4	4	6	5
C	5	5	1	2
D	0	2	1	1
E	0	0	0	0

<u>Comments:</u>

Full HUD Symbology Set

Pilot 12: Remove aircraft symbology.

The Basic/RWY HUD Symbology Set

No comments were provided.

The Basic/RAW HUD Symbology Set

No comments were provided.

The Basic/BOTH HUD Symbology Set

No comments were provided.

Question 4. Use the Modified Cooper Harper Scale (last page of this package) to rate the workload associated with the Full HUD in each of the following conditions:

a. VMC _____

Full HUD Symbology Set

Table C-10. Frequency of Cooper-Harper Ratings to Question 4a for the Full HUD Symbology Set

Cooper-Harper Rating	Frequency
1	2
2	4
3	3
4	2
5	1
6	0
7	0
8	0
9	0
10	0

Comments:

No comments were provided.

The Basic/RWY HUD Symbology Set

Table C-11. Frequency of Cooper-Harper Ratings to Question 4a Basic/RWY HUD Symbology Set

Cooper-Harper Rating	Frequency
1	2
2	4
3	4
4	2
5	0
6	0
7	0
8	0
9	0
10	0

Comments:

No comments were provided.

The Basic/RAW HUD Symbology Set

Table C-12. Frequency of Cooper-Harper Ratings to Question 4a for the Basic/RAW HUD Symbology Set

Cooper-Harper Rating	Frequency
1	3
2	6
3	2
4	0
5	1
6	0
7	0
8	0
9	0
10	0

Comments:

Pilot 7: Not too annoying, but unnecessary.

The Basic/BOTH HUD Symbology Set

Table C-13. Frequency of Cooper-Harper Ratings to Question 4a for the Basic/BOTH HUD Symbology Set

Cooper-Harper Rating	Frequency
1	5
2	3
3	3
4	0
5	1
6	0
7	0
8	0
9	0
10	0

Comments:

Pilot 7: Don't need it.

<u>Question 4.</u> Use the Modified Cooper Harper Scale (last page of this package) to rate the workload associated with the Full HUD in each of the following conditions:

b. With a sensor image _____

Full HUD Symbology Set

Table C-14. Frequency of Cooper-Harper Ratings to Question 4b for the Full HUD Symbology Set

Cooper-Harper Rating	Frequency
1	1
2	2
3	3
4	3
5	3
6	0
7	0
8	0
9	0
10	0

<u>Comments:</u>

No comments were provided.

The Basic/RWY HUD Symbology Set

Table C-15. Frequency of Cooper-Harper Ratings to Question 4b for the Basic/RWY HUD Symbology Set

Cooper-Harper Rating	Frequency
1	0
2	2
3	2
4	5
5	1
6	1
7	1
8	0
9	0
10	0

<u>Comments:</u>

No comments were provided.

The Basic/RAW HUD Symbology Set

Table C-16. Frequency of Cooper-Harper Ratings to Question 4b for the Basic/RAW HUD Symbology Set

Cooper-Harper Rating	Frequency
1	1
2	4
3	5
4	1
5	1
6	0
7	0
8	0
9	0
10	0

Comments:

Pilot 7: Would like to see flight director.

The Basic/BOTH HUD Symbology Set

Table C-17. Frequency of Cooper-Harper Ratings to Question 4b for the Basic/BOTH HUD Symbology Set

Cooper-Harper Rating	Frequency
1	2
2	1
3	6
4	0
5	3
6	0
7	0
8	0
9	0
10	0

Comments:

No comments were provided.

Question 4. Use the Modified Cooper Harper Scale (last page of this package) to rate the workload associated with the Full HUD in each of the following conditions:

c. With the corner reflectors _____

Full HUD Symbology Set

Table C-18. Frequency of Cooper-Harper Ratings to Question 4c for the Full HUD Symbology Set

Cooper-Harper Rating	Frequency
1	1
2	1
3	1
4	6
5	2
6	0
7	1
8	0
9	0
10	0

Comments:

No comments were provided.

The Basic/RWY HUD Symbology Set

Table C-19. Frequency of Cooper-Harper Ratings to Question 4c for the Basic/RWY HUD Symbology Set

Cooper-Harper Rating	Frequency
1	0
2	2
3	1
4	4
5	3
6	2
7	0
8	0
9	0
10	0

Comments:

Pilot 7: Not too annoying, but unnecessary. Would like to see flight director. Touchdown aim point is ambiguous.

The Basic/RAW HUD Symbology Set

Table C-20. Frequency of Cooper-Harper Ratings to Question 4c for the Basic/RAW HUD Symbology Set

Cooper-Harper Rating	Frequency
1	1
2	4
3	2
4	0
5	5
6	0
7	0
8	0
9	0
10	0

Comments:

No comments were provided.

The Basic/BOTH HUD Symbology Set

Table C-21. Frequency of Cooper-Harper Ratings to Question 4c for the Basic/BOTH HUD Symbology Set

Cooper-Harper Rating	Frequency
1	1
2	3
3	3
4	0
5	4
6	1
7	0
8	0
9	0
10	0

Comments:

No comments were provided.

Question 4. Use the Modified Cooper Harper Scale (last page of this package) to rate the workload associated with the Full HUD in each of the following conditions:

d. Without a sensor image _____

Full HUD Symbology Set

Table C-22. Frequency of Cooper-Harper Ratings to Question 4d for the Full HUD Symbology Set

Cooper-Harper Rating	Frequency
1	1
2	0
3	4
4	2
5	1
6	3
7	0
8	1
9	0
10	0

Comments:

No comments were provided.

The Basic/RWY HUD Symbology Set

Table C-23. Frequency of Cooper-Harper Ratings to Question 4d for the Basic/RWY HUD Symbology Set

Cooper-Harper Rating	Frequency
1	0
2	1
3	2
4	3
5	2
6	1
7	2
8	1
9	0
10	0

Comments:

Pilot 7: Without glidepath information in the initial stages of the approach, excessive mental effort is required to maintain glidepath. Once in close with the sensor, it was excellent and pretty good with the corner reflectors. VMC it was slightly annoying but tolerable. Overall, it is an okay system 1) if used with additional glidepath. information and 2) if runway lines are selectable by the pilot. A fixed value could cause high or low flares depending on the runway width.

The Basic/RAW HUD Symbology Set

Table C-24. Frequency of Cooper-Harper Ratings to Question 4d for the Basic/RAW HUD Symbology Set

Cooper-Harper Rating	Frequency
1	1
2	2
3	2
4	2
5	2
6	1
7	1
8	1
9	0
10	0

Comments:

Pilot 7: Not too annoying, but unnecessary. Would like to see flight director. Touchdown point is ambiguous.

The Basic/BOTH HUD Symbology Set

Table C-24. Frequency of Cooper-Harper Ratings to Question 4d for the Basic/BOTH HUD Symbology Set

Cooper-Harper Rating	Frequency
1	1
2	0
3	4
4	3
5	4
6	0
7	0
8	0
9	0
10	0

Comments:

No comments were provided.

Question 5. Did you experience any clutter problems with the HUD Symbology Sets:

a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

Full HUD Symbology Set

Yes **11** No **1**

Comments:

Pilot 1: In as much as I took time to wonder if there was something I should be paying attention to rather than concentrating on landing the plane.

Pilot 2: Obstructed view of image.

Pilot 3: Too much information, led to stagnated Cross-check.

Pilot 4: Aircraft symbol masks other data/symbology.

Pilot 6: So much data presented, at some instances (flare) it actually was a distraction.

Pilot 7: Too much information tends to wash out runway environment.

Pilot 8: Too much symbology in center.

Pilot 9: Symbols sometimes overlapped, blocking important data.

Pilot 10: Full HUD is very cluttered.

Pilot 11: Confuse some symbols, i.e., A/S worm with runway minimum aircraft blocks out other symbols.

Pilot 12: Aircraft Symbol/Flashing "GND," and "F" Flare

The Basic/RWY Symbology Set

Yes **4** No **8**

Comments:

Pilot 2: Miniature aircraft too large.

Pilot 4: Aircraft symbol clutters HUD.

Pilot 7: Slightly annoying in VMC. Washed out corner reflectors.

Pilot 12: Aircraft Symbol/Flashing "GND," and "F" Flare

The Basic/RAW Symbology Set

Yes **4** No **8**

Comments:

Pilot 2: Too much stuff in central field.

Pilot 4: Aircraft symbol clutters HUD.

Pilot 7: Aircraft pointer is unnecessary.

Pilot 12: Aircraft Symbol/Flashing "GND," and "F" Flare

The Basic/BOTH Symbology Set

Yes **4** No **8**

Comments:

Pilot 2: See general comment sheet.

Pilot 4: Aircraft symbol clutters HUD.

Pilot 5: I like the runway symbol as you get on short final (i.e., inside 1/2 mile). It is most useful here for aligning the aircraft with the runway.

Pilot 7: Standard (aircraft nose pointer not necessary).

Pilot 12: Aircraft Symbol/Flashing "GND," and "F" Flare

Question 5. Did you experience any clutter problems with the HUD Symbology Sets:

b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

Full HUD Symbology Set

Yes **11** No **1**

Comments:

Pilot 1: In my opinion, there was much more information depicted than necessary to safely fly the approach and land the plane. Get rid of the course steering cue circle.

Pilot 2: Hard to discern small deviations.

Pilot 3: Too much information, led to stagnated cross-check.

Pilot 4: Aircraft symbol masks other data/symbology.

Pilot 5: "VanHalen" symbol was sometimes distracting. Runway symbol would sometimes be superimposed on the raw data localizer course. Caused confusion.

Pilot 6: Speed worm and acceleration cue a distraction.

Pilot 7: High mental effort required to interpret all of the information presented.

Pilot 9: Symbols sometimes overlapped, blocking important data.

Pilot 10: Full HUD is very cluttered.

Pilot 11: Confuse some symbols, i.e., airspeed worm with runway minimum aircraft blocks out other symbols.

Pilot 12: Aircraft Symbol/Flashing "GND," and "F" Flare

The Basic/RWY Symbology Set

Yes **4** No **8**

Comments:

Pilot 2: Miniature aircraft too large.

Pilot 4: Aircraft symbol clutters HUD.

Pilot 5: Sometimes confused runway symbol with localizer course raw data.

Pilot 12: Aircraft Symbol/Flashing "GND," and "F" Flare

The Basic/RAW Symbology Set

Yes **4** No **8**

Comments:

Pilot 2: Miniature AIRCRAFT and course interfere with raw data.

Pilot 4: Aircraft symbol clutters HUD.

Pilot 7: Aircraft pointer is unnecessary.

Pilot 12: Aircraft Symbol/Flashing "GND," and "F" Flare

The Basic/BOTH Symbology Set

Yes **7** No **5**

Comments:

Pilot 1: More than 5 miles out, the dotted course line, raw data line, the heading marker, and the runway outline depiction all melded together.

Pilot 4: Aircraft symbol clutters HUD.

Pilot 5: Confused CDI with runway at times.

Pilot 7: Standard (aircraft nose pointer not necessary).

Pilot 8: Runway symbol was tall and skinny and could easily be confused with raw data.

Pilot 12: Aircraft Symbol/Flashing "GND," and "F" Flare

Question 6. Was there any necessary information missing from the any of the HUD Symbology Sets:

a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

Full HUD Symbology Set

Yes **2** No **10**

Comments:

Pilot 7: No FAF marker (or MM) information was presented. Flight director only provided vertical information; it should do both vertical and horizontal.

Pilot 10: Turn/slip.

The Basic/RWY Symbology Set

Yes **8** No **4**

<u>Comments:</u>

Pilot 2: Course indicator.

Pilot 4: DME.

Pilot 6: Course glideslope.

Pilot 7: See previous comments.

Pilot 8: Raw data would help.

Pilot 9: I would not want to fly a low-visibility approach without raw data.

Pilot 10: Wind vector and DME.

Pilot 11: Maybe not...wasn't sure how to use it.

Pilot 12: See videotape.

The Basic/RAW Symbology Set

Yes 5 No 7

<u>Comments:</u>

Pilot 2: DME winds, etc. Would be useful.

Pilot 3: Runway would have helped.

Pilot 4: DME.

Pilot 7: Not "necessary" but flight director ball is desirable.

Pilot 10: DME and wind.

Pilot 12: Steer to vs. deviation from.

The Basic/BOTH Symbology Set

Yes **3** No **9**

<u>Comments:</u>

Pilot 2: DME, winds would be helpful.

Pilot 4: DME.

Pilot 10: Needle/ball, DME and wind.

Pilot 12: See videotape.

Question 6. Was there any necessary information missing from the any of the HUD Symbology Sets:

b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

Full HUD Symbology Set

Yes **4** No **8**

Comments:

Pilot 1: I needed something to break altitude complacency. The radar altimeter and barometric altimeter decision heights should double in size or change color (green for approaching, yellow at altitude ± 20', red going below)

Pilot 4: DME.

Pilot 10: Turn/slip.

Pilot 12: Better lateral steering to localizer . . . mechanize pitch symbol "o" to ⊗ or (see drawing), and have it give steering to localizer and glideslope.

The Basic/RWY Symbology Set

Yes **10** No **2**

Comments:

Pilot 2: Course indicator DME and winds.

Pilot 3: Location/glideslope.

Pilot 4: DME.

Pilot 5: More precise course and glideslope deviation information.

Pilot 8: Course and glidepath.

Pilot 9: I would not want to fly a low-visibility approach without raw data.

Pilot 10: Course/glidepath data.

Pilot 12: See videotape.

The Basic/RAW Symbology Set

Yes **6** No **6**

Comments:

Pilot 1: Altitude alerting indicators. Reference ground speed depiction.

Pilot 2: DME, winds, etc. would be useful.

Pilot 4: DME.

Pilot 10: DME and wind.

Pilot 12: Steer to vs. deviation from.

The Basic/BOTH Symbology Set

Yes **5** No **7**

Comments:

Pilot 1: Reference ground speed. Altitude warning system.

Pilot 2: DME, winds would be helpful.

Pilot 4: DME.

Pilot 6: DME.

Pilot 10: Needle/ball, DME and wind.

Question 7. Was there any unnecessary information provided by the full HUD:

a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

Full HUD Symbology Set

Yes **11** No **1**

Comments:

Pilot 2: Raw ILS, flight director cue.

Pilot 3: Numerous approach guidance items were no longer of use. Flare, GND, rising runway were nice, but unnecessary.

Pilot 4: Aircraft symbol and runway symbol.

Pilot 5: "VanHalen" and "Speed-worm."

Pilot 8: Having reference mark "GND" flash.

Pilot 9: I found these symbols useless (see questionnaire for drawing).

Pilot 10: Flag, circle, worm, carat, runway, rising runway, GND, and FLARE.

Pilot 11: Speed worm and acceleration cue redundant-simulator hype.

Pilot 12: Aircraft symbol and see videotape.

The Basic/RWY Symbology Set

Yes **2** No **10**

Comments:

Pilot 4: Aircraft symbol.

Pilot 7: Aircraft nose pointer.

The Basic/RAW Symbology Set

Yes __4__ No __8__

Comments:

Pilot 2: Min. AIRCRAFT symbol.

Pilot 4: Aircraft symbol.

Pilot 7: Aircraft pointer is unnecessary.

Pilot 8: No comment.

Pilot 9: The vertical dotted line of the (see questionnaire for drawing) symbol.

Pilot 10: Raw data not needed for landing phase.

The Basic/BOTH Symbology Set

Yes **5** No 7

Comments:

Pilot 2: Using both just clutters image.

Pilot 4: Aircraft symbol, runway symbol.

Pilot 6: See my HUD Assembly Task selections.

Pilot 7: Standard (aircraft nose pointer not necessary).

Pilot 9: Same as before, the dotted vertical line and the (see questionnaire for drawing) symbol.

Pilot 10: Runway, raw data and source selected.

Question 7. Was there any unnecessary information provided by the full HUD:

b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

Full HUD Symbology Set

Yes **11** No **1**

Comments:

Pilot 1: Get rid of the acceleration trend pointer, make the aircraft reference marker smaller and less cumbersome.

Pilot 2: RAW ILS, flight director cue.

Pilot 3: Airspeed markers are duplicative; should have either/or far digital or reel-tape.

Pilot 4: Aircraft symbol and runway symbol.

Pilot 5: VanHalen, speed worm and pointer., runway (at least on long final).

Pilot 9: I found these symbols useless (see questionnaire for drawing).

Pilot 10: Flag, circle, worm, carat, rising runway GND, FLARE.

Pilot 11: Speed worm and acceleration cue redundant-simulator hype.

The Basic/RWY Symbology Set

Yes **3** No **9**

Comments:

Pilot 4: Aircraft symbol.

Pilot 7: Aircraft nose pointer.

The Basic/RAW Symbology Set

Yes **4** No **8**

Comments:

Pilot 3: Aircraft nose is not important.

Pilot 4: Aircraft symbol.

The Basic/BOTH Symbology Set

Yes **7** No **5**

Comments:

Pilot 2: Using both creates confusion.

Pilot 4: Aircraft symbol, runway symbol.

Pilot 5: Runway symbol is not real useful on long final.

Pilot 8: Runway symbol.

Question 8. Were there any safety issues associated with any of the HUD Symbology Sets:

a) When a sensor image/visual scene was available? Yes _____ No _____ If yes, explain.

Full HUD Symbology Set

Yes **6** No **6**

Comments:

Pilot 2: Miniature aircraft symbol shouldn't be dominant. Pitch scale slaved to flight path marker.

Pilot 3: Task saturation with other events could be hazardous.

Pilot 6: Distraction from primary task...land the airplane.

Pilot 7: Only that there is too much information.

Pilot 9: Regardless of the clutter and symbol overlapping, it's not hard to look past the extra symbols to get the needed data.

Pilot 10: Clutter complicates HUD interpretation.

Pilot 11: Momentarily confuse symbols after a short distraction, speed worm, runway symbol. Have to work back to get proper interpretation.

The Basic/RWY Symbology Set

Yes **7** No **5**

Comments:

Pilot 2: Lack of perspective/runway centerline could be a problem with large course deviations.

Pilot 3: Centerline control was not sufficient for safe correcting if the pilot wanders.

Pilot 6: See previous comments and HUD building exercise.

Pilot 7: Lack of GP information.

Pilot 8: Not suitable for precision approaches without raw data available.

Pilot 9: Without raw data and with imprecise glidepath guidance, flying an approach into mountainous terrain could be a problem.

Pilot 10: Without glidepath deviation indicator, it is likely that a dragged-in approach/short landing could result.

Pilot 11: I didn't crash.

The Basic/RAW Symbology Set

Yes **1** No **11**

Comments:

Pilot 2: Raw data representation doesn't give clear intuitive picture of required corrections.

The Basic/BOTH Symbology Set

Yes **0** No **12**

Comments:

No comments were provided.

Question 8. Were there any safety issues associated with any of the HUD Symbology Sets:

b) When a sensor image/visual scene was not available? Yes _____ No _____? If yes, explain.

Full HUD Symbology Set

Yes **5** No **7**

Comments:

Pilot 2: Minimize Aircraft symbol; shouldn't be dominant. Pitch scale slaved to flight path marker.

Pilot 3: Pilot workload and cross-check stagnation.

Pilot 5: Clutter was an issue, but probably not to the point that it was unsafe.

Pilot 7: Too much information.

Pilot 10: Clutter complicates HUD interpretation.

Pilot 11: Momentarily confuse symbols after a short distraction, speed worm, runway symbols. Have to work back to get proper interpretation.

The Basic/RWY Symbology Set

Yes **10** No **2**

Comments:

Pilot 1: Contrast between the green depictions of the HUD and the bright white background was a serious problem.

Pilot 2: Lack of perspective/runway centerline could be a problem with large course deviations.

Pilot 3: Excessive lateral displacement as well as vertical deviation can develop.

Pilot 5: I flew two approaches to the over-run because the glideslope information from the runway symbol is not sufficiently precise.

Pilot 6: Only workload necessary to correct approach errors.

Pilot 7: Lack of GP information.

Pilot 10: Without glidepath deviation indicator, it is likely that a dragged-in approach/short landing could result.

Pilot 11: Okay, maybe I did.

The Basic/RAW Symbology Set

Yes **3** No **9**

Comments:

Pilot 2: Raw data representation doesn't give clear intuitive picture of required corrections. No reference for angle off from runway heading.

Pilot 6: Contrast issue, again in "No Sensor" cases.

Pilot 10: Hard to judge transition to land.

Pilot 12: Poor pitch/vertical decent information.

The Basic/BOTH Symbology Set

Yes **2** No **10**

Comments:

Pilot 2: Confusion factor.

Pilot 6: Contrast in "No Sensor" cases.

Question 9. What strategy did you incorporate for each of the HUD Symbology Sets in the precision approach task?

Full HUD Symbology Set

Pilot 1: Focusing on the raw data ILS. information, the depicted wind component, the airspeed readout, and the flight path marker.

Pilot 2: Work hard to minimize deviations without visual/sensor image. In VMC, use same offset to see runway.

Pilot 3: Ignore many items. Concentrate on flight path vector. Occasional cross-check at airspeed.

Pilot 4: Flew raw data ILS.

Pilot 5: Ignore "VanHalen" and runway symbol. Fly raw data and flight director commands.

Pilot 7: Selectively incorporate only the symbols that provided me with the information I wanted into my cross-check.

Pilot 8: Use raw data for azimuth and glidepath (marker cue had too much lag). Acceleration and speed symbol for power.

Pilot 9: Ignore useless symbology.

Pilot 10: Mental: ignore clutter.

Pilot 11: Don't allow deviations to get too big...correct as soon as possible.

Pilot 12: Full pitch steering cue and monitor alignment with runway symbology.

The Basic/RWY Symbology Set

Pilot 1: Wait until the desired landing point passes between the manual glidepath line (the dashed line) then put the flight path indicator on that desired landing point. Be aware of actual aircraft heading vs. runway heading.

Pilot 2: Very intuitive to fly. Normal cross-check.

Pilot 3: Work hard.

Pilot 4: Flight path symbol on runway symbol at 3° ↓

Pilot 5: Strive to keep the runway symbol vertical and aimed for just past the approach end of the runway symbol.

Pilot 6: Try to get on corrections early.

Pilot 7: Pay close attention to 3-D location (especially GP) using available information.

Pilot 8: Keeping the FPM where I wanted to land on the runway symbol while checking the adjustable horizontal reference with runway symbol. Cross-checking airspeed.

Pilot 9: Line up the dashed "3 degree" line with the runway symbol's "captain's bars."

Pilot 10: Used visual techniques (which by the way, are unreliable in IMC.)

Pilot 11: Make small corrections to see what happened if I didn't like what I saw...did something else.

Pilot 12: Stayed on left edge of runway symbol.

The Basic/RAW Symbology Set

Pilot 1: Nail down the course, glidepath and airspeed, then center the flight path indicator in the crosshairs.

Pilot 2: Keep errors as small as possible.

Pilot 3: Fly like an ILS.

Pilot 4: Raw data ILS.

Pilot 5: Position flight path marker to keep course and glideslope deviation indicators centered.

Pilot 6: Again, get on corrections early.

Pilot 7: Pretty much flew it like an F-16 approach.

Pilot 8: Flew it like a heads down ILS with a standard cross-check.

Pilot 9: Fly it like a regular airplane!

Pilot 10: Standard cross-check.

Pilot 11: Small corrections. Keep those little guys centered.

Pilot 12: Stay as close to "on-track" as possible.

The Basic/BOTH Symbology Set

Pilot 1: Same as for the Basic HUD with raw data only.

Pilot 2: Flew the runway symbol and cross-checked the raw data.

Pilot 3: Fly an ILS approach, but cheat to the runway as if it were VMC.

Pilot 4: Raw data ILS.

Pilot 5: Flew mostly raw data. Started using the runway symbol on short final to line up for touchdown.

Pilot 6: Look at it like a "magic eye" picture. The 3D perspective was a big help when added to the raw data.

Pilot 7: No strategy necessary. Fly it as presented.

Pilot 8: Flew like a heads-down ILS first disregarding runway symbol looking more at runway symbol below 500 ft AGL.

Pilot 9: Fly it like a regular airplane.

Pilot 10: Standard cross-check.

Pilot 11: Small corrections. Keep those little guys centered.

Pilot 12: Line up with left side on runway symbol.

Question 10. Please provide any additional comments or design alternatives that you may have regarding each of the HUD Symbology Sets.

Full HUD Symbology Set

Pilot 1: The HUD concept in general is great! I like looking forward to where I'm going to land while having all the performance feedback right in front of me too. Whatever you do, keep the flight path indicator and add a reference ground speed in just below actual ground speed.

Pilot 2: See general comment sheet. After test complete, suggest trying Full HUD minus miniature Aircraft, ILS raw data and flight direction symbol.

Pilot 3: Have color options for better contrast.

Pilot 4: For the limited number of flights accomplished, I was not at the level of proficiency that I could appreciate the speed worm or the acceleration cue. I suspect that after more hours of experience, I would begin to notice more of the subtleties of the system such as this.

Pilot 7: See previous suggestions. Additionally, heading scale is too large. You could shrink it down a little. There should also be some way of

telling the pilot that ILS information is present and being monitored (e.g., glideslope - On; localizer - On).

Pilot 8: Generally, it was very good. Aircraft display (waterline) was too large (see questionnaire for diagram).

Pilot 9: In the F-16, after touchdown, a vertical bar appears on our display depicting runway centerline. In CAT III conditions, this bar is invisible. I suggest replacing your vertical dotted line with a centerline indicator.

Pilot 10: Orange color for night/IMC without sensor.

Pilot 12: See questionnaire for diagram.

The Basic/RWY Symbology Set

Pilot 1: By far the easiest, but least precise of the HUD depictions to use.

Pilot 2: Needs course indication and additional performance information, but very easy to fly.

Pilot 3: Good pure VMC work.

Pilot 7: Some features need to be added. Reference my optimum configuration on the videotape.

Pilot 8: Needs raw data to give pilot assurance that approach is safe.

Pilot 10: Use orange for the no sensor condition.

Pilot 11: Needs work.

Pilot 12: Delay it from coming on until (see questionnaire for symbol drawing) 100 feet AGL. At decision height, have it flash 3 or 4 times then go out of view. This will prevent continuing the approach below minimums.

The Basic/RAW Symbology Set

Pilot 1: Really nice to work with that system! The best, most precise and in some respects, easiest to work with.

Pilot 2: Hard to develop a mental picture of relationship of course to raw data where the flight path marker should be moved to make appropriate corrections.

Pilot 3: Good starting point.

Pilot 8: Interpreting azimuth (course) was initially confusing...deciding which way to steer when off course. Suggest lateral guidance with a flight path marker cue.

Pilot 10: Instead of raw data, use flight director.

Pilot 12: Workload too high.

The Basic/BOTH Symbology Set

Pilot 2: See general comments.

Pilot 3: Near perfect configuration.

Pilot 8: Leave runway symbol out of the HUD until below about 500 feet AGL.

Pilot 9: The runway symbol is a nice addition to the new data, but it's not necessary when a radar "sensor" is available or any other kind of "actual" runway image.

Pilot 10: Orange for day ILS, needle/ball, DME, wind and flight director.

Pilot 12: Delay runway symbol and eliminate it at decision height.

Some General Questions

The HUD Symbology Sets

Question 1. Overall, which HUD configuration did you *most* prefer? Why?

Table C-25. HUD Symbology Set Preference Frequencies

	Basic/RWY	Basic/RAW	Basic/BOTH	Full
Frequency	1	4	4	3

Comments:

Pilot 1: The Basic HUD with Raw Deviation Data. Easiest to read with the most precise information.

Pilot 2: Runway Symbol. Clear, easy to use, uncluttered, but could be improved.

Pilot 3: Basic both Runway and RAW.

Pilot 4: Basic HUD with Raw Deviation Data.

Pilot 5: Almost a toss up between Raw and Raw with runway. These configurations provided the right mix of information without too much clutter.

Pilot 6: Full HUD...could fine tune easier.

Pilot 7: Basic HUD with both Runway and Raw Data...it provided the best combination of information without too much cluttering (there was some).

Pilot 8: Full. Although it was a bit cluttered, it was eerier and the speed/acceleration cues were especially helpful.

Pilot 9: Basic HUD with raw data. For me it's the easiest display to fly.

Pilot 10: Both - maximum data, minimum clutter.

Pilot 11: RAW data only. All information in there. Is similar to flying ILS.

Pilot 12: Full. Most detail.

Question 2. Overall, which HUD configuration did you *least* prefer? Why?

Table C-26. The Frequencies for Least Preferred HUD Symbology Set

	Basic/RWY	Basic/RAW	Basic/BOTH	Full
Frequency	5	1	0	6

Comments:

Pilot 1: The Full HUD. Too cluttered, took too much time to cross-check and interpret the data.

Pilot 2: Full HUD. Too much clutter...even interfered with VMC. Very uncomfortable in touchdown zone.

Pilot 3: Basic with Runway.

Pilot 4: Full HUD; too cluttered.

Pilot 5: Full too busy. Often got symbols confused.

Pilot 6: Runway only...too subtle on cues.

Pilot 7: Full HUD...too much information made it cluttered and took too many brain cells to interpret all of the presented information.

Pilot 8: Basic with Runway Symbol...it looked interesting, but does not provide pilot with enough information about course and glideslope for safety until close in.

Pilot 9: Basic HUD with Runway Symbol.

Pilot 10: Full too cluttered.

Pilot 11: Runway only. Harder to interpret and to make corrections. Have feeling something is missing, but it apparently works.

Pilot 12: Raw Data. Easy to confuse data.

Question 3. Did you experience any problems associated with the design and mechanization of any of the individual HUD symbols? If so, please explain.

Comments:

Pilot 2: Didn't fully understand relationship of course and runway symbols until after test was over. Rate of heading tape movement very

distracting. Hard to get peripheral items in cross-check because they're so far out. Bank pointer and miniature AIRCRAFT symbol really bad.

Pilot 3: The Yaw indicator on the flight director was only cute...no useful purpose. The flight director piper tracked with the aircraft vector, this was confusing at times...require second order interpretation. Roll indicators at top of HUD were too many degrees out-of-view...try the bottom half instead.

Pilot 5: "VanHalen" symbol seemed too big to the point that it could be a distraction. It seems its primary purpose is to indicate the difference between aircraft heading and track (for crab condition). I can get the same information from my heading and the CDI. Better, yet, it might be useful to add a "drift" readout. (For example, a 4° R drift indication would require a 4° L crab.)

Pilot 6: Acceleration caret, speed worm, "GND" symbol on/near touchdown. These were by and large distractions. Lack of DME on non-Full HUD cases...when incorporated...on Full HUD case...too far in upper left corner.

Pilot 7: The flight path marker needs a definite reference for its center (see questionnaire for drawing). The flight director ball should be mechanized to do both azimuth and elevation functions.

Pilot 8: Yes. Aircraft reference symbol was too large/too apparent for its usefulness. Suggest a single line (see questionnaire for diagram). Flight path marker cue possessed too much lag and did not provide lateral guidance; reduce lag and provide lateral guidance.

Pilot 9: The (see questionnaire for drawing) symbol seemed to float around aimlessly. All it did was get in the way of other more important symbols. I completely ignored the vertical dotted lines, and lastly, the small circle didn't provide any useful information.

Pilot 10: Flag...useless; small circle...useless; acceleration cue...marginal utility; speed worm...marginal utility; aircraft reference bar...too wide/thick.

Pilot 12: Aircraft symbol cluttered data. See questionnaire for drawing.

The TRAC Simulator

A. **Very acceptable:** A good simulation as is.

B. **Moderately acceptable:** Minor simulation deficiencies exist that do not impact pilot performance.

C. **Borderline:** Simulation deficiencies exist that could impact pilot performance; improvements would be desirable.

D. **Moderately unacceptable:** Simulation deficiencies degrade pilot performance; improvements required.

E. **Very unacceptable:** Simulation is too deficient to provide the intended function.

Question 1. Flight characteristics _____

Table C-27. TRAC Simulator Flight Characteristics - Rating Frequencies

Rating	Frequency
A	3
B	6
C	1
D	2
E	0

Comments:

Pilot 8: Yoke freeplay was excessive! Was too much Dutch roll!

Pilot 12: Directional control and yaw was poor!

Question 2. Throttle characteristics _____

Table C-28. TRAC Simulator Throttle Characteristics - Rating Frequencies

Rating	Frequency
A	3
B	6
C	1
D	2
E	0

Comments:

No Comments were provided.

Question 3. Out-the-Window display _____

Table C-29. TRAC Simulator Out-the-Window Display - Response Frequencies

Rating	Frequency
A	7
B	3
C	2
D	0
E	0

Comments:

Pilot 7: Limited by database to only whole degrees.

Question 4. Sensor image representation _____

Table C-30. TRAC Simulator Sensor Representation - Rating Frequencies

Rating	Frequency
A	7
B	4
C	1
D	0
E	0

Comments:

Pilot 7: Excellent.

Question 5. HUD representation _____

Table C-31. TRAC Simulator HUD Representation - Rating Frequencies

Rating	Frequency
A	6
B	5
C	1
D	0
E	0

Comments:

Pilot 7: Only bad case is WX only.

Question 6. Cockpit geometry _____

Table C-32. TRAC Simulator Cockpit Geometry - Rating Frequencies

Rating	Frequency
A	4
B	4
C	2
D	2
E	0

Comments:

Pilot 1: Throttle quadrant too far back.

Pilot 7: No heads down stuff to reference.

Question 7. Were you able to adapt to the simulator aeromodel in a reasonable period? Yes _____ No _____. If No, please comment.

Yes **11** No **1**

Comments:

No comments were provided.

Question 8. Were the random winds adequate at inducing a nominal amount of pilot control in order to remain on course and glideslope? Yes _____ No _____.

Yes **11** No **1**

Comments:

Pilot 10: Sinusoidal variation is inappropriate...results in sustained oscillation and is not realistic.

Question 9. Was the Out-the-Window scene commensurate with your experience with approaches in low visibility conditions? Yes _____ No _____. If No, please comment.

Yes **11** No **1**

Comments:

Pilot 2: Visuals okay, but lack of peripheral vision is a limitation.

The ALG Concept

Question 1. Do you think there is a future for ALG in the major commercial passenger and freight industry? Yes _____ No _____. Comments:

Yes **11** No **1**

Comments:

Pilot 3: More likely to be automatic and autonomous.

Pilot 4: I don't think it will replace CAT III auto-land approaches.

Pilot 8: Absolutely.

Pilot 9: Although auto-pilot coupled GPS approaches seems to be where we're headed, some sort of heads-up "sensor" image would implement this system perfectly.

Pilot 10: Best thing since instruments...fighters (F-111) had it...awesome capability.

Pilot 12: Add: Angle-of-path information and sell a "windshear/energy management" program.

Question 2. Using an ALG display similar to the one in this evaluation, would you be comfortable flying low visibility approaches? Yes _____ No _____. Comments:

Yes **10** No **2**

Comments:

Pilot 2: Display improvement required. Sensor image adequate if it can achieve that fidelity in all WX conditions.

Pilot 3: I'm never comfortable flying in low visibility situations!

Pilot 4: Particularly for a coupled approach, I think the HUD would enhance safety.

Pilot 7: With the modifications to the HUD to reduce clutter.

Pilot 11: Am I flying or monitoring the auto pilot?

General Comment Sheet

Pilot 2: Placement of bank pointer is distracting. When flying the FPM as primary, you have to search for pointer. Doesn't help that it is a long way off.

The course indicator is useless and a hindrance when flying ILS approach. With the HSI implementation, the course indicator gives feel for orientation to runway, but doesn't observe central area needed for deviation indication. The HUD implementation doesn't give feel for orientation...only whether right or left.

The miniature aircraft symbol is way too large and (poorly shaped) to enhance FPM-based system.

Lag in flight director cue is unacceptable. Doesn't appear to be just lag in some cases, but extremely slow movement rate or "gain" to make adequate correction.

How is the horizon/heading tape implemented? The pitch sensitivity is very good, but the heading constantly sliding by at high rate is very distracting.

The full display is much too cluttered for normal VFR operation.

The runway symbol perspective is minimal and barely effective at preventing anything during final approach.

Radar ALT is in useful position. Airspeed and ALT too far from center.

Corner reflector presentation helps with perspective.

Using the steering bar presentation with the glidepath/touchdown zone presentation seems awkward to me. I think there may be a way to optimize the glidepath touchdown zone presentation with a similar lateral presentation to be overall more consistent with T-PM.

See questionnaire for drawings. This position is a wag with the current symbology because the dotted lines aren't there. If they were a periphery or center with opposite location containing target values, then computation would be automatic. With good enough perspective on runway symbol (and extended center line) the CDI approach might not be needed at all.